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Energy Management System Benchmarking for a Remote Microgrid

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A mis padres, por apoyarme incondicionalmente y enseñarme a alcanzar mis objetivos.

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Resumen

El presente trabajo analiza el efecto que tiene la estrategia de control adoptada en el sistema de gestión de energía de una microrred en el rendimiento económico y el impacto medioambiental asociado a su operación.

Las microrredes aisladas son una solución para la electrificación de áreas remotas que debido a su localización geográfica no pueden ser conectadas a la red eléctrica. La estructura de estos sistemas permite la integración de energía proveniente de generación distribuida, principalmente renovable. El abaratamiento de los colectores fotovoltaicos, el autoconsumo y los incentivos medioambientales ofrecidos a este tipo de generación son algunos de los factores que impulsan la adopción de este tipo de redes.

Sin embargo, los retos técnicos asociados a las microrredes con un alto índice de penetración renovable hacen necesario un sistema de gestión de la energía que se adapte a las necesidades del sistema. Asimismo, para garantizar un suministro eléctrico de calidad e ininterrumpido, es necesario el uso de sistemas de almacenamiento eléctrico, que el sistema de control deberá gestionar adecuadamente tomando en consideración las previsiones de la demanda y solares.

Como caso de estudio se ha tomado la isla Isabela, situada en el archipiélago de Galápagos al oeste de Ecuador. A partir de octubre de 2017 esta isla contará con un sistema eléctrico conformado por 922 kW de generación solar, 1625 kW de generación térmica y un sistema de almacenamiento de baterías Ion-Litio de 258kWh de capacidad. A través de la simulación de tres estrategias de control se pretende analizar que controlador se adapta mejor a las necesidades del sistema.

Abstract

This documents analyses the effect the control strategy followed by the energy management system of a microgrid has on is economic performance and the environmental impact associated to its operation.
Isolated microgrids appear as a solution to the electrification of remote communities that due to their geographical location cannot be connected to the main grid. The architecture of this systems enables the integration of electricity generated from distributed energy resources, in particular renewable generation. The decrease in prices of solar PV collectors, self consumption and the economic incentives given to clean energy generation in many countries are pushing forward the adoption of this kind of electrical grids.
However, the challenges associated to the operation of microgrids with a high index of renewable penetration require an energy management system that is designed around the specific needs of the system. Moreover, in order to guarantee the quality and continuity of the supply, the use os energy storage systems is necessary, which will need to be managed appropriately by the energy management system, taking into account the demand predictions and the solar forecast.
The island Isabela, which belongs to the Galapagos archipelago located west from Ecuador, has been taken as a case study. From October 2017 the islands electrical system will from an energy mix of 922 kW solar PV,1625 kW diesel generators and a 258 kWh Lithium-Ion batteries storage system. Through the simulation of three control strategies the aim is to determine which controller is most suitable for the control operation of the island.

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1 Introduction

1.1 Introduction

Environmental and economic incentives have been pushing renewable energy technologies forward for the last decades, however the variable nature of these resources complicates their integration into the grid. Due to the recent international climate agreement achieved in the Paris Climate Conference in 2015, is foreseen an increase in the use of renewable energy is foreseen all over the world to offset the carbon emissions already produced. Microgrids are an emerging solution for the integration of distributed renewable resources that first appeared described in [8] as a ”subsystem of generation and associated loads”. The main characteristic of microgrids is that during disturbances they can isolate from the distribution network without harming the transmission grid’s integrity.
Microgrids combined with renewable energy can be a solution not only for the integration of renewable energy in developed countries but also for emerging economies as well as for the electrification of remote areas. Galapagos is an example of the last: the archipelago is a protected ecosystem located 900 km west of Ecuador. The islands constitute a World Heritage site, due to the high number of marine and bird species that inhabit it, and their whole economy revolves around tourism. To protect them and ensure their conservation, the government of Ecuador took the initiative to reduce the fossil fuel dependency of the islands and in this way decrease the risk of fuel spilling in their coasts. Since 2007 several renewable generation systems have been installed in San Cristobal, Santa Cruz and Floreana islands. The last addition, a hybrid system in Isabela, is scheduled to go into operation by October 2017. However, due to the increasing population and electrical demands of the islands, the installation of more clean energy technologies will be required soon if the government wants to keep up their green energy policy.
Due to the remote locations of the islands, and considering the objective to increase renewable penetration, microgrids appear as a solution to manage the local loads and generation in a coordinated way.
The special characteristics of microgrids, specially in those that are isolated and cannot relay on a main grid, require an energy management system different from the ones used in conventional electrical networks to dispatch electricity generation. Energy management systems can also be designed to answer to the specific needs of the grid, giving priority to specific types of technologies.

1.2 Objectives

This thesis has two main objectives. The first one is to develop a state of art on microgrids and their energy management systems(EMS). The second one consists on applying this concepts to the island Isabela in the Galapagos archipelago, and make a comparison of the results from using three different energy management systems that follow different dispatch strategies.
The state of art on microgrids and the special characteristics of their EMS is seen as a research project to give an answer to the lack of condensed knowledge on the topic. Although it has been over a decade since Lassester first mentioned

microgrids in [8], there are few textbooks on the matter and the publications found are very disperse and most of them are focused on specific case studies.
The impact of the EMS on economic efficiency, continuity of supply, and renewable penetration is studied by comparing the dispatch results from three different strategies. The main objectives in doing so are to achieve the highest possible renewable penetration, reduce GHG emissions and be economically efficient.

1.3 Software and Tools

Two software programs have been used in the making of this study: HOMERPro and MATLAB.
MATLAB has been used to implement one of the EMS that will be studied in Section 4, and for this aim the version R2015b of 32 bit was installed. Regarding HOMER Pro, the version 3.7 has been used with the advanced license. HOMER Pro has been used to model the microgrid in Isabela, including the load and the components that compose it. Two of the energy management systems analysed where integrated in the software, whereas for the third one HOMER Pro worked combined with MATLAB.

1.4 Stages of development

The development of this work has been carried out in four stages. The search and reading of documentation took around 140 hours. The design of the system and the simulations took 80 hours, the analysis of the results took 40 hours and the writing of this document took around 100 hours.

1.5 Structure

The second section will cover the state of art on microgrids. It is divided into three subsections, each dedicated to microgrids architecture, energy management systems and forecast methods of the solar resource respectively. The first part covers the definition of microgrid typical microgrid structure, its component, the advantages microgrids present against conventional grids and and overview of the studies that have been carried out internationally on the application of microgrids.
The second part goes over the different types of control architectures in a microgrid, the hierarchical levels in the control, and the challenges EMS have to face when applied specifically to microgrids. It also presents a compilation of different real case applications of microgrids EMS. In the last part forecast has been included because of the high influence it has in achieving an efficient operation of the system.
The third section presents the electrical situation of the island: the background of the archipelago, the technology installed and the regulatory framework that covers any activity in the electrical sector. It also includes a presentation of the software used: HOMER Pro and MATLAB.
The fourth section goes over the characterization of the load curve in Isabela, the design of the system in HOMER Pro and the analysis of the results obtained from the simulations. An explanation of the EMS implemented in MATLAB is also made to justify the results obtained. This section along with section two, constitute

the core of this work. Section five will give an overview in the socioeconomic framework of the project and finally section six will present the conclusions.

2 State of Art: Microgrids and Energy Management Systems

2.1 Microgrids

According to the U.S. Department of Energy, a microgrid is defined as "a group of interconnected loads and distributed energy resources (DERs) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes" [9] [10].
Another definition, according to [11], would be a set of generation devices, storage systems and loads that are connected to the same low or medium voltage grid, which in turn is connected at the Point of Common Coupling (PCC) on the main distribution grid.
From the first definition we can withdraw three characteristics DER installation must comply in order to be considered microgrids: they must have electrical boundaries clearly defined, there must be a master controller to operate DERs and loads, and the installed generation capacity must be higher than the peak critical load in order to allow the disconnection from the main grid.
According to [12] there are four types of microgrids:

- Institutional/Campus microgrids: focused on the aggregation of existing on site generation with multiple loads that are located on the same campus or institutional setting.
- Remote microgrids(stand-alone): This microgrids never connect to the main grid and operate in islanded mode all the time. There is usually a geographical and economic reason behind them, as they can be both remote locations of difficult access or islands. This will be the type of microgrid studied in this document.
- Commercial and industrial microgrids: this type of microgrid can be found in North America and Asia, but the lack of well-known standards limits their expansion. As they are still emerging they do not have clear characteristics.
- Military base microgrids: These microgrids are being deployed with special focus on physical and cyber security in order to guarantee reliable power without relaying on the main grid.

The concept of a microgrid first appeared in 1882, when Thomas Edison founded his first power plant. This would be the first one out of the 50 DC microgrids he built over four consecutive years. However, when the utility grid emerged large centralized power plants took over and the concept of the microgrid faded away.

2.1.1 Microgrid Structure

There is not a universal list of the components that form a microgrid, but it can be commonly stated that a microgrid will be formed by several components that are not usually found in traditional grids [13]. These components include loads, DERs, master or central controller, smart switches, as well as telecommunication and control systems. Figure 1 shows the typical structure of a microgrid.

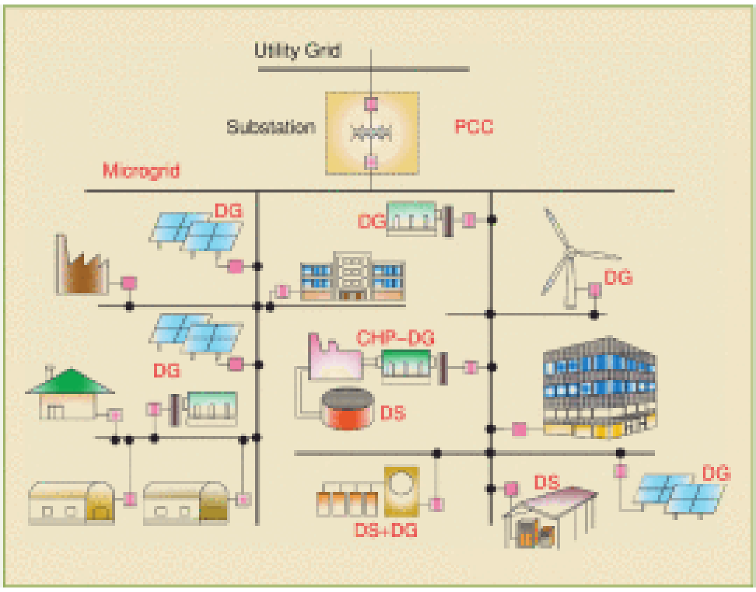


Figure 1: Microgrid Structure [1]

Loads Microgrid loads can be classified as flexible or fixed loads. Flexible loads are those that can be subject of demand side management or load shedding, whereas fixed loads cannot be altered. Flexible loads play a key role in microgrids with increasing levels of renewable energy penetration, as they can be used as a tool to match supply and demand.

DERs Distributed energy resources (DERs) comprise both distributed generation units (DG) and distributed energy storage systems (ESS). A distributed generator can be defined as a small scale electric power generator directly connected to the distribution system close to the load feeder [13]. This can refer to several energy techologies such as diesel engines, micro turbines, fuel cells, PV, wind turbines or storage units[14]. On contrast, traditional means of power generation are based on centralized power plants, which generate electricity far away from the consumers. This electricity is then transported through high voltage transmission lines to reach local areas. Due to the closeness to consumers, some DGs present CHP applications, and can generate simultaneously heat and power, reaching an efficiency of up to 85% [13].
As they do not relay on a transmission network DER technologies are suitable to generate electricity in isolated areas where transmission and distribution facilities are not available. In addition DERs require a lower construction and deployment time than centralized power plants.

Distributed Generation (DG) Microgrid DG units can be either dispatchable or non-dispatchable. Dispatchable units are those that can be controlled and are subject to technical constraints such as capacity limits, both minimum and maximum, ramping, fuel and emissions limits. Non dispatchable units, which mainly comprise renewable energy technologies, generally solar and wind, are characterized by the intermittence and volatility in their power output. The intermittent nature of these input sources implies that the distributed generation (DG)

units cannot be controlled by the master controller. To compensate for this lack of regularity and reduce its negative impact on the nonsdipatchable generation unit, energy storage systems (ESS) are applied. The storage technologies reduce uncertainty and forecast error.
According to [9], two common categories of DERs used in microgrids for the last years are renewable DGs and ESSs. These are mostly wind and solar energy. The trend indicates an increasing use of this technologies associated to the environmental advantages they present unlike fossil energies, and their role in the mitigation of climate change defined by international energy policies and agreements[15]. Renewable energy is highly dependant on the weather which is unpredictable in the long term, and this results in uncertainty and volatility in the production. On the other hand they are sustainable, environmentally friendly technologies with zero emissions.
Many solar energy applications use maximum power point tracking to optimize their production. For a given solar radiation, the MPPT finds the unique point of the voltage-current characteristic that maximizes the power output, and sets the solar cells to work at this point.

Energy Storage Systems (ESS) The volatile nature of the renewable DG resources requires a power source that can absorb some of this variability and compensate for this fluctuations. This could be a dispatchable energy source such a gas turbine but also a energy storage system. ESS allow a smooth transition between connected and isolated modes, moreover they add flexibility to power generation, consumption and delivery. In [16] a system that combines renewable energy technologies with battery storage systems is presented. The aim of the paper is to develope a control strategy folowing the rule-based control scheme for a system based on the BESS makes these intermittent renewable energy sources more dispatchable.
However, the objective for ESS use varies depending on the microgrid operational mode. When it is in islanded mode the ESS can provide power to minimize the disturbance on consumers and maintain the system reliability. When the microgrid is in interconnected mode, the distributed energy storage is in charge of maintaining a good power quality by assuring its stability, and also storing low price energy based on real time pricing of electricity and time tariffs. In this way, ESSs can not only improve the supply quality but also increase economic efficiency, as they enable the storage of low cost energy but at the same time can be operated as DGs during the peak demand periods [13].
ESSs also provide utility grids with several improvements. Large scale ESS increase the efficiency of the grid, reducing operation costs ad emissions and increasing power reliability [9]. Conventional power plants cannot respond to fluctuations in demand or in the output of volatile generations fast enough, as they have a large thermal inertia. For this reason, with increasing levels of renewable energy penetration the need on ESS becomes more important, as we can not relay on thermal plants to compensate for fluctuations. ESSs can store the surplus of renewable energy production and supply this energy when there is no wind or sunshine. In this way, the power generation from volatile sources can become continuous and reliable.

In [17] an energy management system strategy is proposed based on a stand alone system with distributed battery storage. The battery storage makes it possible to avoid the use of communication cables and the costs associated to them. The strategy modifies the traditional droop method so that the power can be unbalanced, allowing the regulation one or more batteries based on the requirements.

Smart switches and controllers Other outstanding components are smart switches and protective devices. When a fault takes place they isolate the problem area so that it does not affect the rest of the grid. The point of common coupling (PCC) is an specific switch that connects or disconnects the microgrid from the utility grid. The last function is usually referred to as islanding. However, it is the master controller that defines the interaction with the microgrid and sends an order for connection or disconnection to the PCC.

2.1.2 Microgrids Advantages

Dependig on their operation strategy microgrids offer many and diverse economical, environmental, technical and social benefits. We can find a classification of these benefits in [18], based on the EU R&D project *More Microgrids*.

Economical Benefits The economical benefits of microgrids can be divided in two subcategories: those providing locality benefit and those providing selectivity benefit. Locality is related to the economical benefits derived from having a local grid energy market that can interact or not with the main grid. Selectivity is due to the optimization in real time of energy dispatch decisions to minimize the opportunity cost of the microgrid taking into account the environmental and technical limitations.

- The microgrid can provide local retail and market services.
- The microgrid can be regarded as a hedging tool against energy price volatility,change in load or outage.
- The microgrid could act as an aggregator for both supply and demand side services.
- The microgrid could act as a mediator between the different parties interested.

Technical Benefits Regarding technical advantages, [9] enumerates the value propositions of microgrids. These include improved reliability, resiliency, power quality and energy arbitrage, all of which result in economic benefits. [19] also points out the efficient integration of conventional power plants with renewable sources, minimized operational costs and reduced costs in T&D for supply to remote areas. However the actual level of technical benefits is dependent on the optimality of the microsources allocation and the degree of coordination between the different agents.

Reliability System operators and electric utilities constantly seek to increase the grid reliability. It resembles how often is the grid available for consumers use. There are several ways to monitor the grid reliability, commonly through the interruption frequency or the average interruption time [20]. Outages are caused by meteorological phenomena, failures in T&D lines etc., and they affect the grid reliability.
However, microgrids can significantly improve this indexes, due to their ability of islanding. In this way, the smart systems of the microgrid, which inlcude both control and automation systems, and the use of DERs allow the islanding operation when a fault is detected in the main grid, and therefore the consumers of the microgrid will suffer reduced interruption times. Moreover, the proximity to the consumers loads also reduces the probability of a failure in the T&D lines affecting the supply. This increase in reliability can be converted into economic benefits through the decrease in 'Energy not supplied'.
According to [9], microgrids studies related to reliability can be classified according to two different perspectives: evaluation and improvement. The studies that take the evaluation perspective asses islanded microgrids with renewable distributed generation, for example considering the probabilistic behaviour of solar and wind power. [19] is particularly interesting as it carries out a study on both the reliability and economical outcomes of two different microgrid configurations. The result of the study is that the operating costs of the microgrid are considerably reduced when they are in interconnected mode, as this allows it to trade energy with the grid to achieve the most optimal dispatch. Regarding reliability, it shows that the SAIFI and SAIDI indexes, which represent the system average interruption frequency and duration respectively, improve remarkably in a microgrid that uses DERs compared to one which does not. The studies that focus on the improvement of reliability propose many ways to do so such as coupling microgrids, adding renewable DG or cooperation between the main grid and the hydro and wind sources of the microgrid.

Resiliency Resiliency is the ability to resist a failure and rapidly recover from breakdown, and it has a direct impact over the grid reliability. These failures are usually caused by weather events and meteorological hazards, as well as by cyber security attacks. [21] is a report written by the U.S. Department of Energy that points out the importance of electricity outages in monetary terms and seeks to modernize the grid and improve its resiliency. Climate change is increasing the frequency and intensity of severe weather, and therefore resiliency is becoming increasingly relevant. In this context, microgrids are considered part of the solution, once again due to the key characteristic that is their ability to isolate from the main grid, and that would minimize the damage caused by one of this events. Moreover they can benefit from energy storage, which increases the stability of the system.

Power Quality The requirements of consumers regarding power quality have become more demanding in the past decades due to the increase in voltage sensible loads and LEDS. Microgrids provide an efficient solution to power quality need by implementing local control of voltage, frequency, loads and compensation

through the use of energy storage systems.
Other advantages include:

- Energy loss reduction due to decreased line power flows.
- Relief of congested networks, for example during peak periods.

Environmental and Social Benefits The environmental benefits of microgrids are associated to the possibility to integrate energy from renewable DERs, allowing the shift towards cleaner technologies, and to the adoption of more energy efficient solutions [18] [14].
Social benefits are expected from:

- Raising public awareness about energy efficiency and GHG emissions.
- Creations of new jobs and research positions for technology providers, device manufacturers, research institutes etc.
- Electrification os isolated or developing areas.
- Reduced carbon emissions thorugh the use of renewable DERs

2.1.3 Recent Studies

So far microgrids have mostly established as test-bed platforms belonging to R&D projects carried out by developed countries, that are interested in the potential social and economical advantages microgrids can offer. These include countries in Europe, the United States, Canada and Japan.

European Union
The EU has carried out two R&D projects on microgrids since 1998. The first one, *Microgrids: Large Scale Integration of Micro-Generation to Low Voltage Grids*, elapsed from 1998 to 2002 and some of its most important objectives were to study the operation of microgrids both in interconnected and islanded mode, develop control strategies to ensure an efficient and reliable operation of the microgrids, study the use of microgrids to increase renewable penetration and decrease carbon emissions, and identify and develop the required telecommunication infrastructures [22]. This project was led by the National Technical University of Athenas in collaboration with other utilities, and it successfully provided several technical solutions. For instance, DER models, islanded and interconnected operation philosophies, hierarchical and distributed control algorithms, methods of quantifying reliability or laboratory microgrids of various complexities.
The second project, *More Microgrids: Advanced Architectures and Control Concepts for More Microgrids* elapsed from 2002 to 2006 and it aimed to investigate new micro sources, storage and local controllers to increase efficiency, develop alternative control strategies and alternative network designs, look into the commercial and technical integration of microgrids, standardise the commercial and technical protocols and hardware and study the impact on the power system operation and on the development of electricity networks. It was led again by NTUA, but also counted with the support of research teams in the UK, France, Spain, Portugal and Germany [23]. Three demonstration sites were built, in Germany, Greece and

the Netherlands. Both the systems in Greece and Germany studied the application in residential use. The system in Kythnos Island (Greece) provided power fro 12 houses, combining 10 kW of PV, a 53 kWh battery bank and a 5 kW diesel generator. A second PV system with a 32 kWh battery was installed to provide power for monitoring and communication. The system in Germany aimed to get the consumers involved with load management. During two months, 20 families and a day-care centre participated in the project, shifting their consumption according to the PV output availability information provided for their neighbourhood. In addition to the previous more demonstrations were carried out in Spain, Portugal, Denmark and Italy.

United States

The United States have an expanding microgrids research program, supported by the Department of Energy and the California Energy Commission. The most well-known project was pursued under e Consortium for Electric Reliability Technology Solutions (CERTS). It started on 1999 to study the effects on reliability of the emerging technology. In 2002 the concept of *CERTS Microgrid* was developed, and it intended to separate from the utility grid during disruptions to assure the power supply to critical loads.The viability of the CM has been testes in simulation and in a laboratory scale test in the University of Wisconsin. An outstanding feature of this project is that it has simultaneously developed tools necessary for microgrid implementation. The main products are *μGrid Analysis Tool* and *The Distributed Energy Resources Customer Adoption Model* . *μGrid Analysis Tool* was created to provide an electrical analysis adequate for the CERTS Microgrid that could not be provided by the existing analysis tools. This was due to the unique characteristics of this microgrid, such as that it might contain three-phase, single phase and two-circuit secondary circuits systems, as well as a variety of sources interconnected by power electronic devices. it enables the prediction and evaluation of imbalances, asymmetries, the estimation of stray voltages, and the dynamic interaction of the various components and its effect on the system stability, frequency control and dynamic voltage control. *The Distributed Energy Resources Customer Adoption Model* is and economic model with the objective of minimizing the cost of operating on site generations and CHP systems.[22]

Japan

Japan is the world leader in microgrid demonstration projects. NEDO (New Energy and Industrial Technology Development Organization) is the research and funding of the Ministry of Economy, Trade and Industry, and it started three demonstration sites in 2003 under its *Regional Power Grid with Renewable Energy Resources Project*. These sites are Aomori, Aichi and Kyoto. The *Aomori Project* was in operation between 2005 and 2008 and it evaluated for PQR, cost effectiveness and GHG emissions reductions. the central feature of this project is that it only used renewable resources. It served seven buildings in the city of Hachinohe and the energy management system developed during t project met optimally the buildings demand for both electricity and heat. The *Aichi Project* was the first NEDO demonstration, and it was situated close to the Central Japan Airport. It supplied a Tokoname City building ad a sewage plant, and used a combination of different fuel cells. Last of all, the *Kyoto Project* waas the fisrt virtual microgrid demonstration project and it covered 40 km span. It used 50 kW of PV, 50 kW of wind turbines, five 80 kW biogas gensets, a 250 kW molten carbonate fuel cell ad a 100 kW battery bank. An energy control centres communicates with the DERs using the internet protocol and a telecom network to enable the balance of demand and supply.

Canada

The RD&D prjects in Canada are focused in Medium Voltage microgrids. Two applications of microgrids have been evaluated, remote microgrids and grid-connected microgrids. In Canada remote applications apply to electrically non integrated areas, typically inaccessible communities. Until now they had been generating power autonomously exclusively with diesel gensets. Microgrid applications study the reduction of fuel costs and aim to develop field experience with planning and operating autonomous distribution grids that use a variety of energy resources.On the other hand, the objective the grid-connected projects it to investigate the full scale development, demonstration and performance assessment of frequency a voltage control methods, the transition between islanded to connected modes, and high DER penetration and its impact on the utility grid. Moreover, they in 2005 a planned islading demonstration was carried out. A 12 hour islanding of a 11 MW load was achieved successfully. The most important aspects of the experiment were to control and mitigate the transients during the islanding operation, achieve stability based on a generator speed-droop governor control, protection coordination for the island and power quality provision for specific loads during islanded operation. [22]

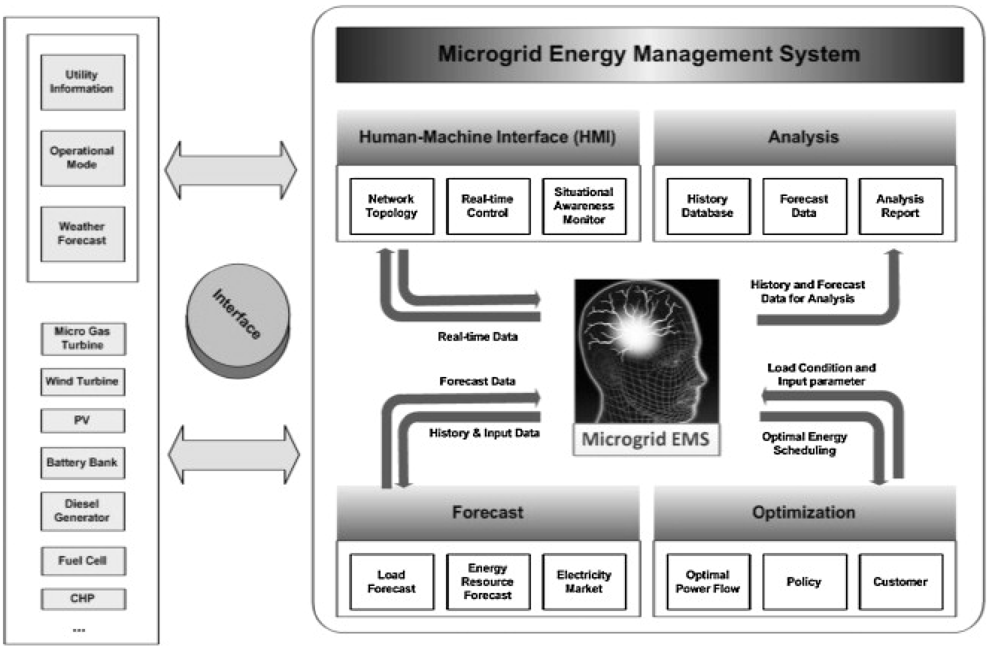


Figure 2: Microgrid EMS Functionalities

2.2 Energy Management Systems

The unique characteristics of microgrids and the dynamics of their components makes a challenge out of them when it comes to their control and operation, and therefore the energy management scheme can be very different from a conventional power plant. This energy management scheme will also depend on penetration of the distributed energy resources.
According to [13], a microgrid energy management system (EMS) is ”a control software that can optimally allocate the power output among the DG units, economically serve the load, and automatically enable the system resynchronization response to the operating transition between interconnected and islanded modes based on the real-time operating conditions of microgrid components and the system status”. In other words, it is responsible for the economical and reliable operation of the microgrid and it is also sometimes referred to as secondary control[11].

2.2.1 Functionalities of a Microgrid EMS

The EMS of a microgrid is expected to monitor the forecasts and operation conditions and optimally dispatch the power generation among the different energy resources to supply the loads, both critical and controllable. Moreover, controllable loads can also be dispatched to ensure the reliability of the system and the supply of critical loads when necessary.
In Figure 2 the functionalities of the energy management system are laid out. It receives load, energy resource and market forecast, real time data, and load conditions. With this information it has to produce a optimal energy schedule, which will include load dispatch, generation schedule, utility power purchases and charging cycles of the DES. It will also store the forecast and history data for future analysis.

2.2.2 Microgrid EMS Control Architecture

In an energy management system three hierarchical levels are defined:

1. Distribution network operator (DNO) and market operator (MO).The DNO is higher level management system that collects real time information from several microgrids and coordinates them. The MO exchanges information with the microgrid about the electricity market and energy prices.
2. Microgrid Central Controller (MGCC).
3. Local controllers, which are associated to each DER unit.

In Figure 3 LC, GC and SC, represent the local controllers for the loads, generation and storage units respectively.
The DNO and MO are on the top and will exchange information withe the MGCC. Depending on the configuration between MGCC and LCs two different control architectures have been described in the literature: centralized and decentralized.

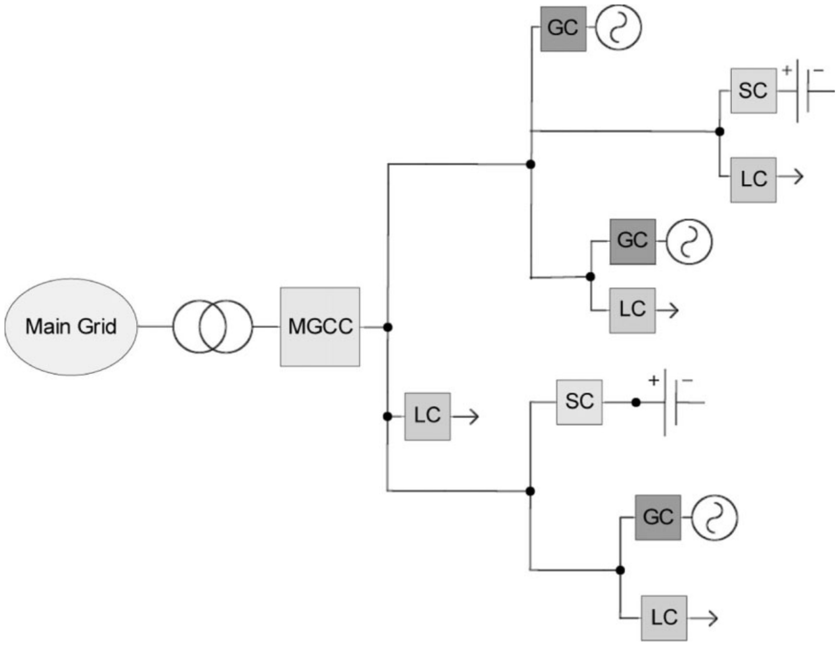


Figure 3: Microgrid Control Structure

Centralized Microgrid EMS
Ideally in a centralized microgrid the EMS will be integrated in the MGCC, which will have two functions. On one hand, it will communicate with the upper level, to meet the supply requirements and take part in the energy market. The MGCC tracks the operational conditions, responds to disturbances and can switch between interconnected and isolated modes.

On the other hand, the MGCC exchanges information with the LCs. It receives

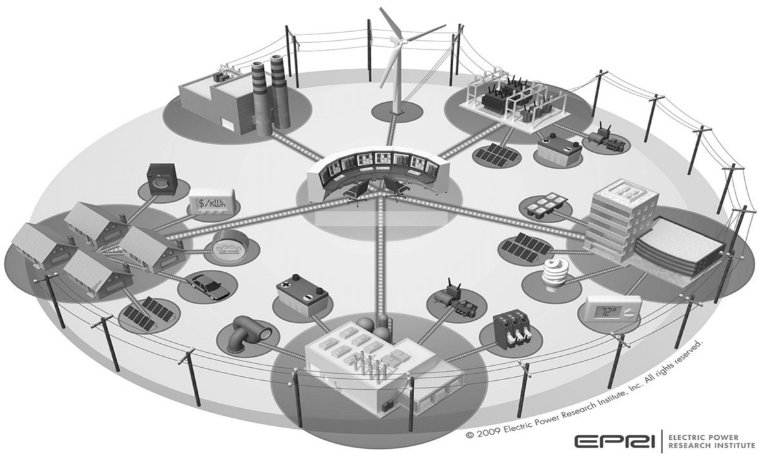


Figure 4: Centralized Microgrid EMS

real time data on their operational state and their requests, and given the system set point defined by the DNO it optimally allocates the power output among the DERs according to the objective function defined in the EMS. This objective function can aim to maximize profit, minimize the batteries charge cycles or maximize renewable energy penetration, depending on the energy management strategy followed. Then the MGCC sends back the control signals to the LCs and

their corresponding generation units. it is important to highlight that the entire allocation process is subject to the system constraints, such as renewable resource uncertainties, reserve requirements or minimum load of generators.
The advantages of this approach are its easy implementation, the standardized procedure, allowing a broad observability of the microgrid, and the suitability for application of optimization techniques. However the large amount of data exchanged not only requires the MGCC to be computationally powerful but also implies that both this computational ability ot communication network can easily become the bottleneck of the system, specially as the number of devices increases. Another disadvantage is the reduced flexibility as the EMS need to be modified in order to incorporate more generators. This characteristics also make them suitable to operate in islanded mode. [13] [24]
Centralized microgrid EMS were implemented during the early adoption of microgrids. In [24] the conceptual design of a centralized EMS and the its desirable attributes for stand-alone operation are described. The proposed EMS requires forecast on the load and generation and embodies two main blocks, a multi-stage economic load dispatch block and a unit commitment block.

Decentralized Microgrid EMS
Contrary to centralized control, the decentralized EMS allows almost autonomous

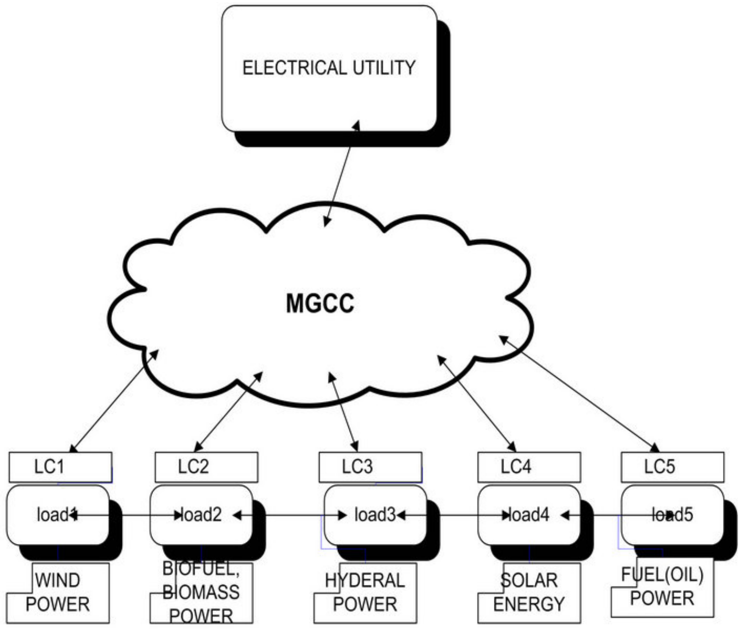


Figure 5: Decentralized Microgrid EMS

operation of the generation units. in this architecture each microgrid component is regulated by one or more local controllers instead of being subject to the MGCC. Every local controller monitors and communicates the other local controllers. With the information exchanged they can make operational decisions on their own instead of receiving orders from the MGCC. So each LC exchanges information with other adjacent LC until consensus is reached. As the LC only need to communicate with the neighbouring devices the flow of information is reduced and so it the computational capacity required.

Even so, the MGCC still plays a role in this architecture, as it is the link with the DNO and MO. It exchanges information on energy price, and it can take over control of the LC in the case of an emergency.
The decentralized EMS advantages are a lower computational requirement, reduced information flow, higher flexibility because it is a modular system and allows *plug-and-play* which facilitates the addition of new generation units . However, because LC have more information this makes the microgrid more vulnerable to cyber and physical attacks. Moreover,they require a high level of coordination between LCs and in order to obtain successful communication between them the telecommunication facilities need to be upgraded. The cost of upgrading the communication network and the control facilities are the drawback of this model.[13] [24]
[11] proposes a system architecture that uses decentralized multi-agent system (MAS) technologies to implement the EMS of the microgrid. Given the characteristics of decentralized microgrids, they have often been approached using MAS technologies. A MAS is a system where different intelligent agents, provided with local information, cooperate with each other to achieve multiple global and local objectives [25]. In this case the agents are the local controllers. The paper describe a secondary control implemented through a market system based on energy bids. When the microgrid is operating in grid-connected mode the objective of the EMS it to meet the requirements set by the main grid, when in islanded mode, the objective of the control system is to maintain the frequency close to its reference value.

2.2.3 Microgrid Islanding

Although microgrids in remote geographical regions operate constantly under stand-alone mode, the salient feature of microgrids is precisely their ability to switch between grid-connected and islanded modes. This is done with the switches upstream of the PCC.
During grid disturbances, the microgrid transfers to islanded mode to maintain a reliable supply to the consumer loads supplied by the local DERs. During this time the MGCC keeps the frequency and voltages at the admissible levels, and once the fault is solved is in charge of the resynchronization with the grid. During the resynchronization is crucial to ensure that the microgrid voltage and frequency are synchronized with the utility grid, otherwise current peaks could arise causing severe damage to the system.

2.2.4 Challenges for Microgrid EMS

Although microgrid present many advantages over conventional energy generation their control system can present many difficulties [13]:

- *Dynamic energy supply*: contrary to conventional generation, microgrids topology an be highly dynamic and include many heterogeneous devices. Moreover, plug-and-play increases even more the variability in the topology. As often DGs and DESs are locally owned, consumers can operate their DER units to supply their own load or to provide ancillary services. In addition, controllable loads can also be curtailed or shifted to assure reliability of the supply. The principle of plug-and-play capability is increased flexibility and scalability, but it also introduces a higher level of complexity to the system. Furthermore, the dynamic interaction of several microgrids might involve a complete new arrangement of the microgrid network topology. To do this, it is required to install reliable switches and breakers.

- *Renewable energy intermittency*: Even though one of the most appealing features of microgrids is that they provide a better way to integrate renewable energy, the variability associated to must of this resources complicates microgrid operations. This variability and uncertainty need to be carefully considered during the EMS design.
- *Other uncertainties*: with increasing control loads, load forecasting is becoming more challenging. Traditionally, the forecast was a function of time. However, as the system evolved towards the smart grid model and with the introduction of the electric vehicle the uncertainty regarding load forecast becomes not only temporal but also spatial. Now it is necessary to forecast both when and where the load will be connected, and therefore the EMS must temporal ans spatial scales.
- *Communication network requirements*: In microgrids a good communication network is required to monitor and manage the microgrid components. It must ensure a quality two-way communication, reliability, compatibility between communication technologies and protocols to ensure a successful flow of information between local nodes, time synchronization as some devices require to be controlled in real time, and cyber security. The last is becoming increasingly critical as the use or wireless technologies spreads, because they are more vulnerable to attacks than wired communication networks.

2.2.5 Applications

In [26] a formulation for an intelligent EMS if proposed using artificial intelligence techniques a multiobjective optimization. It analysed the applicability of Artificial Neural Network for short term forecasting, that would allow to predict PV generation 24 hours ahead, and wind power generation and load demand 1 hour ahead. The paper describes in depth for the forecasting method and the Multi Objective Energy Management (MIEM) control, but the forecasting method will be presented thoroughly in the next section. The MIEM uses the Multi Objective methodology, that aims to find the best solution fulfilling different objectives that are usually conflicting one another. In the case studied, the MIEM aims to achieve the minimum cost of operation minimizing as well the GHG emissions, and satisfying at the same time the load balance paying attention to the power generation limits of each DG unit. To find the solution, the objective functions are minimized simultaneously and a decision vector is obtained. This vector contains the solution, in this case the generation set points of each controllable DG unit. It is considered that the vector is optimal is non of its components can be improved without deteriorating at least one of the other components.
[27]describes an EMS for a renewable based microgrid integrated with a water

supply system and a demand side management mechanism. The EMS provides the set points for each generation unit, the operation modes of the water supply system and the signals for the consumers based on demand side management. It minimizes the operational costs while supplying water and electricity demand. For the last, it designs a neural network for two days ahead prediction. this EMS allows a efficient management of the water supply by activating the water pumping as a flexible load, specially during valley periods in the electrical demand. Demand side management is very useful tool to be applied in microgrids EMS, other examples can be found in [28],
[28] proposes a double layer coordinated approach for microgrid EMS. The schedule layer provides and economic operation scheme based on forecast data, whereas the dispatch layer provides power to the controllable units based on real time data. Any difference between forecasting and real time data are solved through the coordination of the two layers. To do so, it reserves the adequate amount of active power in the schedule layer which then is allocated in the dispatch layer. This article also considers the different needs in the system when it is in grid-connected and stand-alone modes respectively. In grid connected in prioritizes the economic profit whereas in stand-alone it focuses on the reliability of the system. In the stand alone mode, in order to keep a reliable supply it integrates all the renewable generation uses demand side management as a back up tool.

2.3 Forecast Methods

There are several reasons why forecast is required for solar energy production: the variable nature of the solar resource, the seasonal deviation in the load demand and production, and the fact that storage systems still have a high cost associated. All this factors have to be taken into account when we want to provide both a flexible and reliable supply.
In order to integrate solar power successfully we need accurate forecasts over different time horizons. Short term forecasts, that can range from seconds to hours, are important for plant operation, real time unit dispatch and grid balancing. Long term forecast are of interest for system operators and utilities when it comes to scheduling and unit commitment.
Here we present a review of the main forecast methods used in solar power forecast.

2.3.1 Regression Models

This traditional methods are based on the extrapolation of long term averaged data to develop a mathematical model for the global hourly irradiance.

Linear stationary models

- Auto regressive models: prediction based on a finite, linear combination of past values.
- Moving average models: weighted average of past values. The weights take into account different factor to which we wish to give more significance, and are usually higher for more recent data.

- ARMA: this model combines the two previous to reduce the number of non useful parameters considered in the series.
- ARMAX: The name of the model stands for "mixed autoregressive moving average with exogenous variables". It takes the previous model a step forward by introducing eternal data to the time series analysed. If we are analysing the solar irradiance, this model could include information about the local temperature, relative humidity, or wind speed and direction, that are independent to the irradiance but affect it.[2]

Non-linear stationary models
The previous model can be converted to non linear models to describe complex behaviour such as chaos. These find an application in the field of artificial networks which are discussed later.
Linear non-stationary models
Non stationary time series have a time dependent nature. While they do not fluctuate around a static mean they do present some kind of homogeneity in their behaviour. They have only been recently been applied in the field s solar radiation and only in the area of research. [2]

- ARIMA
- ARIMAX

2.3.2 Artificial Intelligence

The development of AI techniques began in the 1950s. They aim to imitate the human though and decision making, and can be classified into seven branches:

- Problem solving and planning
- Expert Systems: use f established knowledge for complex decision making.
- Natural language processing: text processing ang generation, speech analysis, machine translation...
- Computer vision: image processing, facial recognition.
- Genetic algorithms: evolutionary algorithms with learning capacity.
- Artificial Neural Networks: Combination of pattern recognition, deductive reasoning and numerical computations to imitate human learning.
- Hybrid system: any combination of the previous.

For solar production forecast only ANN and GA are relevant, and in this document we will focus on ANN.
ANN aim to replicate they way in which a neuron works. Neurons are covered in dendrites, that are structures that stretch out of the cell body and allow it to receive information from other cells and he environment. Similarly, they have one axon, that is the structure that allows the neuron to transmit signals to other neuron's dendrites The neuron regulates the calcium, chloride, potassium and sodium ion levels inside the cell to maintain the electrical potential across the membrane. When the electrical potential becomes larger than a threshold value and electro chemical impulse called action is generated. The action travels down

the axon and triggers communications.
Similarly to reality, artificial neurons ca be connected to form a network. Figure 6

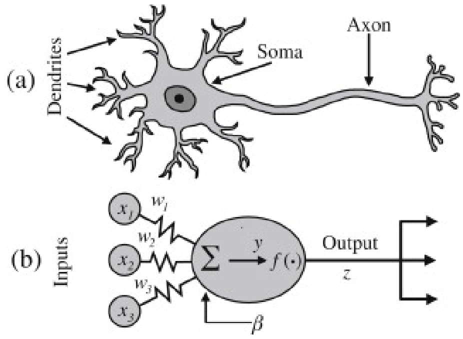


Figure 6: Real and artificial neuron analogy [2]

shows a model of an artificial neuron that takes three inputs from previous neurons and processes them to produce an output z. The weights account for the different relevance of the inputs. β is a variable representing the bias. As a result a transfer function commonly employed is.

$$z = \frac{1}{1 + e^{-(\beta + \sum w_i x_i)}} \tag{1}$$

ANNs can solve a wide range of complex problems, including non linear, non stationary, stochastic mathematical problems with a low level of programming involved.
ADALINE (adaptive linear neuron) is a single logic neuron, however they can be connected in a single layer of inputs and outputs. The problem is that they require a large number of training sets to achieve true convergence. Later on, MADALINE was developed which stands form "many ADALINEs". In addition to the simple input and output layers in basic ANN, MADALINE incorporated additional neural layers, referred to as "hidden" layers. The use of multilayers allowed to solve a wider range of problems starting from the XOR problem. Figure 7 shows a simple

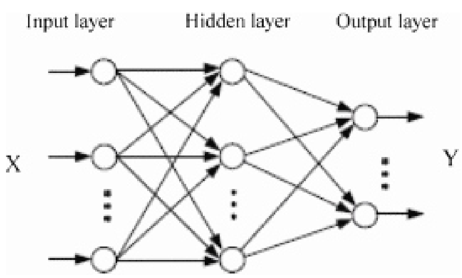


Figure 7: ANN Model [3]

multi layer neural network. The mathematical model aims to get the optimal solution to the following equations:

$$minE(w, v, \theta, \gamma) = \frac{1}{N_1} \sum_{k=1}^{N_1} \sum_{t=1}^{N} [y_k(t) - \hat{y_k}(t)] < \varepsilon_1 \tag{2}$$

$$\hat{y_k}(t) = \sum_{j=1}^{p} v_{jk} \bullet f[\sum_{i=1}^{m} xw_{ij} + \theta_j] + \gamma_t \tag{3}$$

$$f(x) = \frac{1}{1+e^{-x}} \tag{4}$$

Where x is the training data, y_k is the real output, $\hat{y_k}$ is the expected output, w_{ij} and v_{ij} are the weights between neurons. For PV forecasting, the input should be the weather information, coming from numerical weather prediction, and the output should be the output power of the utility. [3]

2.3.3 Numerical Weather Prediction

NWP first started as a combination of the Barotropic Vorticity Equation (Equation 5) and the Electronic Numerical Integrator and Computer (ENIAC) in Maryland in the 1950s. Modern NWP is divided into global and regional, depending on the domain they cover.

$$\frac{\partial \zeta_b}{\partial t} + \bigtriangledown_h \cdot \{(\zeta_b + f)v_\psi\} = 0 \tag{5}$$

NWP provide a longer time horizon than other prediction methods, from 15 to 40 hours.

2.3.4 Applications

The application of ANNs to the field of solar power forecasting has increased since the late 1990s, but is still considered somehow unstable. The changes in data, the architecture of the network, and the weights have a considerable effect on the network training and performance. However researches have chosen a trial and error methodology to deal with this issues.[26]
[29] presents a EMS based on a rolling horizon strategy for a renewable microgrid. It proposes an autoregressive model for the forecast solar irradiance and a neural network for the prediction of the electrical load two days ahead, with one hidden layer. [26] proposes an multilayer perceptron neural network based on the principle of redundancy. I combines different learning machines leading to better generalization performance.[30] also adopts a neural network for the forecast of PV production. The information obtained allows the EMS to make the right decision of whether to store energy or not, giving the system more flexibility a more economically efficient. [31] describes an architectural model of ANNs applied to microgrids. The study designs a neural network for the forecast of the electrical load, and considers real data from Soria in the implementation and testing of the design. The architecture is composed of five modules: historical data, data processing, outlier detection, ANN and the output. The data processing module receives the data from the retrieval system fills in for missing data a produces 15 min data samples, to ge hourly and daily loads. The outlier detection module is in charge of detecting faulty data and eliminating them. The historical data is a database containing all the data handled by the system. The ANN receives information from the historical data module and finally the output is produced.

3 Outline of the Electric Grid in the Galapagos Islands

3.1 Electric Background of the Archipelago

Figure 8: Galapagos Islands($0^o40'00"S$ $90^o33'00"W$)

The Galapagos Islands are an archipelago located in the Pacific ocean, 906 km west from Ecuador, which they are part of. It is formed by 13 main islands, some small ones and over a hundred rocks and islets. 97 % of the island constitutes the Galapagos National Park and only four of the islands are inhabited: San Cristobal, Floreana, Isabela and Santa . Isabela is the largest, accounting for almost 60% of the archipelago's land and with a total area of 4588 m^2 and it is also the only island that strides the equator[32] [33].
The Islands are a volcanic formation, and in fact six volcanoes are found Isabela, five of them active. The geographical location of the islands, their climate and the distance from the continent allowed the formation and evolution of the many animal and plant species that create the diverse habitat that makes this archipelago famous. It is their beautiful natural landscapes and marine life that attracts thousands of tourists every year. In fact the tourism sector has become the basis of the economy in the Galapagos, boosting the revenues of bars, hotels, restaurants, cruises, snorkelling and diving services among others. The tourist activity affects indirectly to all the economy sectors locally in the islands, including the utilization of natural resources, tax collection through the entrance fees to the national park, and is also the main source of income of organizations dedicated to the protection of the environment. As we can see tourism is vital for the local economy, but it also has a negative impact on the ecosystem. With the aim of finding a balance

between both several studies have been carried out and can be found in [34] [35], [36] or [37]. The welfare of the economy depends therefore on the preservation of the environment. For this reason the government of Ecuador has taken several initiatives to reduce the fuel dependence of the islands and make the grid more ecofriendly.
Despite being situated in the equator the islands have a cool and dry climate due to the influence of various air currents such as Humboldt or the trade winds. As a consequence of tropical, the Galapagos enjoy two different seasons: dry ad wet. However, although some years have been exceptions, usually the rainfall is not very persistent during the wet season and there are many sunny days. According

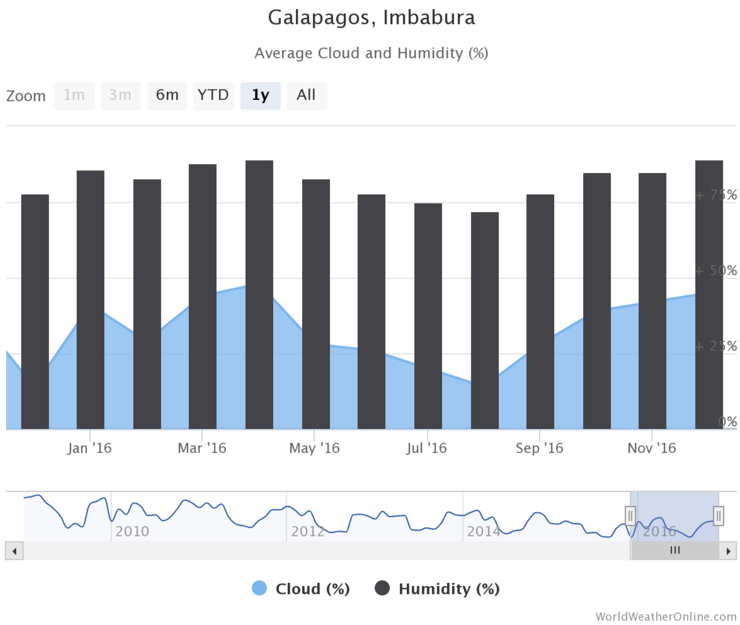


Figure 9: Cloud Cover and Humidity [4]

to the last census, the total population adds to 25244 citizens and is increasing at a rate of 1.8 % annually. About have of them live in Santa Cruz and only 2256 people, 9% of the islands inhabitants, reside in Isabela, mainly in urban areas. Out of the 8436 homes in the islands 99.7% are connected to the electric grid and could be potential clients for our system. [38]
In 2001 an oi tanker ran aground in the coast of San Cristobal spilling over 600000 litres of diesel and fuel oil and damaging the ecosystem in the area and in some other islands, although luckily the ocean ad wind currents limited the damage, keeping it from turning into a great magnitude ecological disaster. Nevertheless, many species were affected and this was the worst environmental disaster recorded in the area. Moreover, it has not been the only shipwreck in the area. Due to the geology of the bay, shallow and with rock formations, many ships have ran aground in it and is known as ”Wreck Bay”. After the incident and in order to mitigate and avoid future accidents, the government of Ecuador has opted for a cleaner energy policy.
It came to an agreement with the cluster of companies GSEP, along with the development program hosted by the UNO, with the objective to reduce the fossil fuels dependency of the archipelago, and in this way reduce also the probability of

another oil spill happening. In reducing the fuel consumption the GHG emissions are also reduced, having a higher positive impact on the environment overall. From this three party agreement, the company Eolicsa (acronym of Wind Energy San Cristobal in Spanish) was founded. Eolicsa n in charge of the operation of the three wind turbines and one of the solar farms built as a consequence of this project. Seven years after the accident they put in place a project to install renewable energy generation in the islands.The project has four parts [39] [40]:

- Wind energy project in Baltra: it consists of three wind turbines rated in 2.25 MW, and able to supply 6 GWh per year to Santa Cruz and Baltra islands.
- Solar farm in Baltra: rated at 200 kW and combined with 900kW storage, specifically hybrid batteries (Li-Ion and Lead-acid). The generation occurrs in Baltra but the electricity will be then transported to Santa Cruz by ELELCGAPALAPOS. Overall it is expected to provide 0.85GWh per year.
- Solar farm project in Puerto Ayora (Santa Cruz): rated in 1.5MW is in charge of the coordination of the renewable energy penetration of the system related to the four individual projects. It provides 22 GWh per year.
- Hybrid system in Isabela: the system will consist of a 1625 kW thermal plant using five dual generators (diesel/pinion oil), a 0.922 MW PV farm, and a 833kW, 258 kWh system of chemical storage using Li-Ion batteries. This project has received financial support from the Government of the Federal Republic of Germany through the German development bank KfW, and is being executed by the Electricity and Renewable Energy Office of Ecuador. For the afore mention execution the consulting firm Lahmeyer International GmbH was hired to manage everything related to studies, final designs, procurement and contracting process, monitoring and technical and economical inspections. The firm also provides services to train, educate, and raise awareness among the locals. The project is foreseen to be ready for operation in October 2017.

From 2007 to 2016 GSEP has operated three wind turbines and a solar farms. They have provided 30% of the electricity demand of the island of San Cristobal, and have saved 8.7 million litres of diesel from 2007 to 2016, reducing also the CO_2 emissions by 2 tons.[41]
Table 1 shows the current power installed in the archipelago and Table 2 summarized the projected capacity for the Hybrd system in Isabela.
It is also worth mentioning that according to [6] the electrical demand in the islands has presented a growing trend during the last decades with an annual growing rate of 9% from 1999 to 2016. Therefore even though the local production is increasing the islands still have a strong dependence on imported energy in the form of oil, and there is still a long way to go before the Galapagos Islands become independent from fossil fuels.

	Nominal Power Installed (kW)			
Island	**Thermal**	**Wind**	**PV**	**Batteries**
San Cristobal	9450	2400	12.5	
Santa Cruz	14950	2250	1567	Ion-Li: 500 kW,268kWh Pb-Acid: 500kW,4032 kWh
Isabela	2640			
Floreana	283		20.9	Pb-Acid: 36kW, 96 kWh

Table 1: Installed Capacity Galapagos [6]

Thermal	**PV**	**Storage**
1625 kW	922 kW	Li-Ion: 833kW, 258 kWh

Table 2: Hybrid System Isabela

3.2 Regulatory Framework

The regulatory framework of all activities related to electricity generation is defined by mainly two pieces of legislation: the *Electric Sector Regime Law* from 1996 and the *Special Regime Law for the Conservation and Sustainable Development of the Province of Galapagos* from 1998, simply known as Special Law of Galapagos. The *Special Regime Law for the Conservation and Sustainable Development of the Province of Galapagos* establishes new regulations and the legal framework to define the migration control and a political decentralization with respect to the central government when it comes to the sustainable development of the region. Moreover, it integrates the common organization inside the political context of the region, therefore reinforcing the concept of participative administration.
This law basically establishes the administrative and legal framework and the basic rules for the establishment of policies and the planning of the Galapagos Islands, which all the agencies of the the region are subject to. This law defines te most fundamental principles for the political decisions on the Archipelago itself. These can be illustrated by the principle of conservation of ecological systems and the native and endemic biodiversity; the sustainable development considering the local ecosystems' capacity for environmental support; the privileged participation of the local community; among others. Because of this law the "National Institute Galapagos" entity (INGALA) was reaffirmed as a "superministry for the development and conservation" of the region. Moreover it assigns faculties and significant obligations to the National Park of Galapagos in the sense that, as a representative of the Environmental Department, it rules the protected territory belonging to the archipelago.
The *Electric Sector Regime Law* defines the bases for the deregulation and opening of the Ecuadorian electric sector. Additionally it establishes some specific points correspondent to the exclusion of Galapagos, from the intention of the Central Governance, to be transferred to the electric firms from the public to the private sector. Under this initiative it is established the Regional Electric Company of

Galapagos (EEPG) as a private firm whose shares are owned by the state.
This legislation also defines the Fund for the Rural and Marginal Urban Electrification (FERUM). This fund is built from specific percentages of the contributions from the sectors that are energy consumers, (trade and industry), which covers the investments in the rural electrification ans specifically in the renewable energy technologies applications. This enables electric firms to access liquid funds, given the approval of CONELEC, for projects related to renewable energy development. In such a way, a financing mechanism is establishes, through the raised funds from all the agents in the electric market, and fro specific ends. Moreover, FERUM sets, by law, that it will have to contribute annually in cash to EEPG in order to offer tariffs consistent with the established ones by CONELEC. This means that CONELEC will allocate, by law, capital funds from FERUM to EEPG to cover the offset of its accounting sheets. This contributions must be considered as guaranteed incomes by law upon which EEPG can count on.
Regarding the environmental duties legislated, CONELEC is entity in charge of technically evaluating the development alternatives to a project in the energy-electric sector. This body will emit the environmental license, and th Ministry of Environment will be able to issue an environmental permit, according to the technical recommendations from CONELEC. To this effect it is necessary to point out that the requirements of the law for this case are described in the " Environmental Regulation for Electric Activities". [42]

3.3 Software used

Two softwares have been employed in the making of this work. In order to model and simulate the electric scenario of the island, HomerPro was used. This program allows us to model the weather conditions, the load demand, and the installed technology in the system, and calculates the optimal dispatch points for each technology according to the system controller that we choose.
HomerPro was used combined with MATLAB for one of the analysed cases. The link between MATLAB and HomerPro allows the user to write a customized EMS that can be integrated as the controller into the simulation. For this aim, the version R2015b-32 bit was required.

3.3.1 HOMER Pro

HOMER is the acronym for "Hybrid Optimization of Multiple Electric Renewables". It is the world's leading microgrid modelling software company, with over 120000 users in 193 countries. It is a micropower optimization modelling software that simplifies that evaluation of designs for isolated and grid-connected power systems. It helps the user to choose the components that must be included in the design and to size them, by presenting the possible configurations and their results.
For this aim it is necessary to provide the software with some inputs describing: the technology options, costs, and resource availability. Then HOMER displays the feasible configurations sorted by cost, but enables the user to see the detailed

simulations results through a series of graphs an tables in other to make the appropriate comparisons and analysis to decide. We will see examples of this results in the next section for our case study.
The program goes through three different phases to provide the results:

- **Simulation**: For each possible configuration of the system, the software simulates the operation of the system by calculating its energy balance in each 1-hour time step over a period of one year. It compares the electric and thermal load demand to the energy available in the system, and assigns the flow of energy from or to each component. It also defines the operation of fuel generator and battery banks if there are any, including the operation set points for the generators, and the charge or discharge rates for the batteries. One each configuration has been simulated HOMER analyses its feasibility, that is, whether in the given operation conditions it can meet the demand or not, and estimates its costs. For the last process capital, O&M , replacement, fuel costs and the interest rate are considered over the lifetime of the project.
- **Optimization**: The configurations are filtrated and ordered according to the user defined criteria. In this process the program applies two algorithms: a original grid sear algorithm and a new HOMER optimizer. The first algorithm simulates all the feasible configuration defined by the search space, and the second which uses a proprietary derivative free algorithm, finds the solution with the lowest cost. Then HOMER displays a table sorted by NPC from smallest to largest to compare the design options in the configurations.
- **Sensitivity analysis**: this is an optional step in which the user can model the impact of different variables. This sensitivity variables are one that are not under our control such as wind speed or component costs. Then HOMER repeats the optimization process considering the range of values defined for the sensitivity variable. This analysis tool is used to study how variations in parameters such as economic conditions and resource availability might affect on the cost effectiveness of each system configuration. The results of the sensitivity analysis help the user to identify the factors that have a largest impact on the system.

HOMERPro also counts with an online database called HOMER Knowledgebase in which the user can look for articles on features of the program. The articles are categorized according to topic, and they are a support tool for the user. This is not the support tool the platform counts with. [43]
The website is another tool users can relay on. It presents links to different resources such as the HOMER energy blog. This blog is a resource in which users exchange tips, opinions and even models. It counts with the active participation of the support team, which reduces the response time. It also presents links to HOMER monthly newsletter, news about the energy industry, an events organized by the company. They also offer online training courses on how to use the software or specific features of it.
Moreover HomerPro counts with participation from the industry, in particular from Danvest, Saft, Xant. It also collaborates with other companies in terms of including information about their components, as is the case of ABB, Bergey Windpower, Trojan or Leonics, among others.[44]

Last of all, it is worth mentioning that HomerPro is a software still in the process of development. Since the fist version was created in 2000 it has undergone many changes. Initially HOMER was a free software created by NREL with updates every few months. In 2014 it officially became HomerPro, turning into a professional software, with the version 3.0 . From this moment on it also stopped being a free access software and since then the updates have been monthly. The version 3.0 completely replaces the version 2.0 adding new features. The MATLAB link feature was released in the version 3.7.0, in July 2016. For this thesis, the version 3.7.6 has been used.

3.3.2 MATLAB link

As we mentioned before, this feature was introduced in 2016 with the version 3.7 of HOMER Pro. It allows the users to write their own dispatch algorithm using MATLAB. To use it, it is required:

1. A version of HOMERPro 3.7 or posterior
2. A 32-bit version of MATLAB (the last 32 bit version was released in 2015)
3. Three MATLAB functions described below
4. To have a HOMER model file with the MATLAB Link Controller option selected in the Controller Set-Up scroll down menu.

This feature belongs to the controller component. HOMER Pro can carry out the simulations using different controllers. Each of them follows a different strategy and seeks to optimize some aspect of the system. The available controllers are:

- **Load following (LF)**: its objective it to meet the demand the for as long as possible, and reduce the interruption time of the system. It also seeks to maximize the renewable energy usage, prioritizing it over other sources. Under this strategy, whenever a generator has to operate it will do so at minimum load conditions.Under this strategy, the storage is charged with power from renewable sources. This strategy is optimal when there is a lot of renewable energy installed and this causes an energy excess in the system.
- **Cycle Charging(CC)**: under this strategy when a generator has to go into operation it will do so at full capacity, an the power surplus is used to charge the batteries. A state of charge set point can e defined, and in that case the charge will not stop until the batteries such level of charge is reached.
- **MATLAB Link (ML)**: this controller reads the strategy form the three MATLAB functions provided by the user.
- **Generator Order (GO)**: The user defines a list with the order by which generators should go into operation. Then HOMER follows the order of generator combinations, and uses the first combination that meets the required operating capacity.

When the ML controller is used, three matlab functions are required, each stored in an individual .m file but all together in the same directory. This three functions are: MatlabStartSimulation, MatlabDispatch and MatlabEndSimulation. The syntax of this functions is defined in the user manual as shown below:

```
[myErr, custom_variables] =
MatlabStartSimulation(simulation_parameters)

[simulation_state, custom_variables] =
MatlabDispatch(simulation_parameters, simulation_state,
custom_variables)

myErrs = MatlabEndSimulation(simulation_parameters,
custom_variables)
```

HOMER calls this three functions before, during, and after the simulation. To run the simulation HOMER goes through the following steps:

1. HOMER creates and sends the variable *simulation_parameters* to MATLAB .
2. HOMER runs the *MatlabStartSimulation* function in MATLAB
3. Homer obtains the variable *myErr* back from MATLAB. If the variable contains any error the simulation is stopped.
4. HOMER creates the empty variable *simulation _state* and sends it to MATLAB.
5. HOMER runs the *MatlabDispatch* function in MATLAB.
6. HOMER recovers the values set by *MatlabDispatch* in the *simulation _state* variable and simulates the timestep according to these values.
7. HOMER updates the values in *simulation _state* for each time step and for each of them, steps 6, 7 and 8 are repeated.
8. After all the time steps have been simulated HOMER runs *MatlabEndSimulation* and any errors are reported back to HOMER. This errors will appear in the user interface.

In this way the variable *simulation _state* is updated in every time step and reflects the operation of the system.

4 MATLAB EMS and Comparison between the three different Controllers

As we mentioned before the results from using three of the different controllers are compared.

4.1 Electric load curve and system description

The Energy Management System developed in MATLAB is based on the current technology installed in Isabela island and its demand, without considering future electric demand scenarios.
Even though Isabela is the largest of the islands in the archipelago it is not the one with more inhabitants and consequently, not the one with more clients connected to the grid. According to [5], in 2016 the number of clients was 1175. Table 3 shows the demand for the Galapagos Islands during the period from 2013 to 2015. As we can see there is a clear increasing trend. Despite the government efforts for the conservation of the ecosystem, the population of the archipelago keeps growing every year. This increase comes from both permanent residents and an increasing flow of tourists, and fluctuates between 4-5% during the last years. Based on this trend, we can find come estimations for future demand in Figure 10.

Table 3: Galapagos Demand Evolution 2013-2015[7]

	2013	**2014**	**2015**
Clients	9.722	10.268	10.781
Demand (GWh)	40.338	47.456	53.896

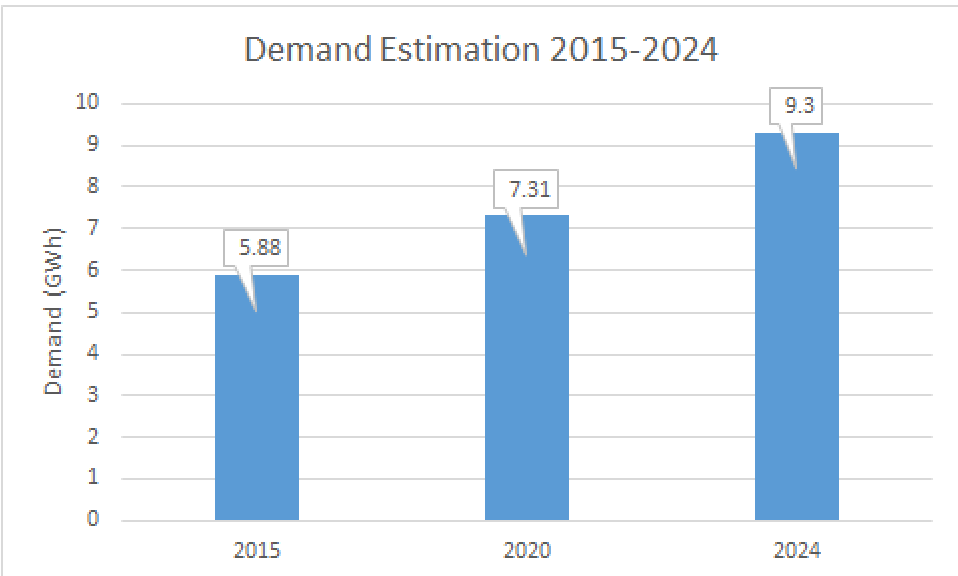


Figure 10: Demand Estimation for Isabela 2015-2024 [5]

It is interesting mentioning that the growth in population will eventually require

the installation of additional power technologies to meet the demand. Considering the green initiatives the government of Ecuador is taking respect to the Galapagos, this will most probably mean there will be great business opportunities for renewable generation as the demand increases. However, for the time being, only the current technology installed will be considered.
From the data from ELECGALAPAGOS for 2015 the demand has been modelled in HomerPro for 2017. The annual demand presents a very similar profile from one year to the next. Moreover, the months with highest peak demand are January, April and November. In HOMER Pro we can model the demand by first choosing the type of load profile (residential, community, industrial or commerical) and then scaling it based on the daily energy consumption. In this case the load profile that best adapts is the community option, and considering that the annual energy consumption for Isabela was 5.88 GWh we can estimate a daily average consumption of 16100 kWh. Based on the available data the monthly demand has been estimated as shown in Figure 11.

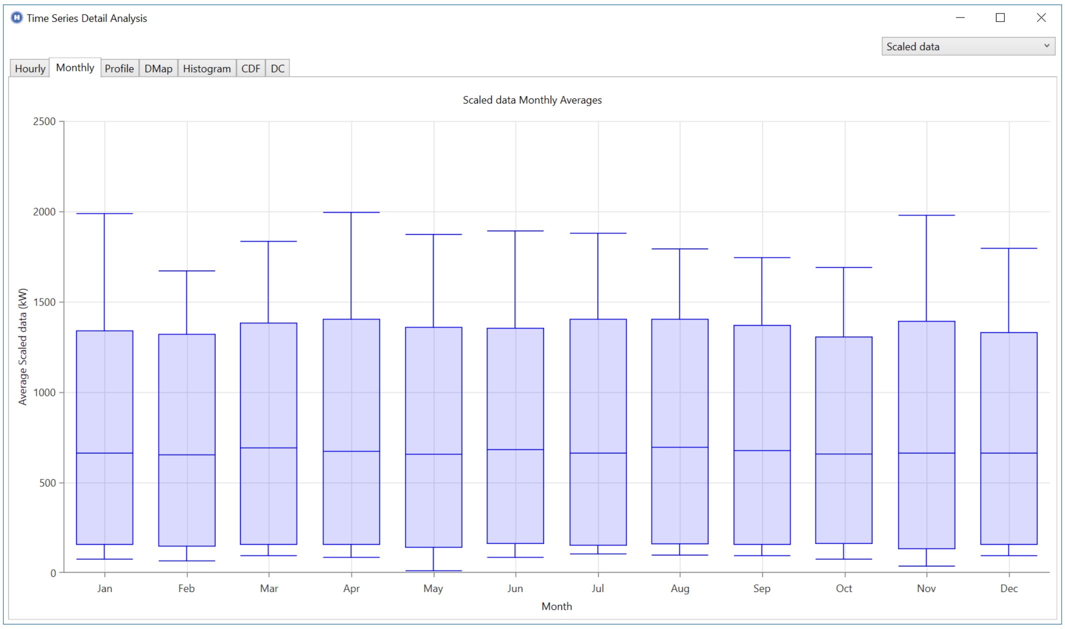


Figure 11: Estimation of Monthly Demand

The demand profile on the other hand, remains quite constant throughout the year as can be appreciated in Figure 12. HOMER Pro considers a day-to-day variability of 10% in the consumption peaks to model these monthly profiles.
At the moment Isabela meets its demand purely with three diesel generators, one model 3512 and two C18 of the brand Caterpillar. However the government aims to loose this dependency on diesel and move towards a renewable energy system. As it was presented in subsection 3.1, Isabela will soon start the operation of the Hybrid System. With this system the island will count with 1625 kW of thermal generation, 922 kw of PV and a 833kW/258 kWh Li-Ion battery bank, as is summarized in Table 4. The total power installed therefore will add up to 3.38 MW. In this study, the new generation system will be considered.

Other factors to take into account when modelling the system are the fuel costs and the meteorological data. The fuel costs in particular, is crucial when

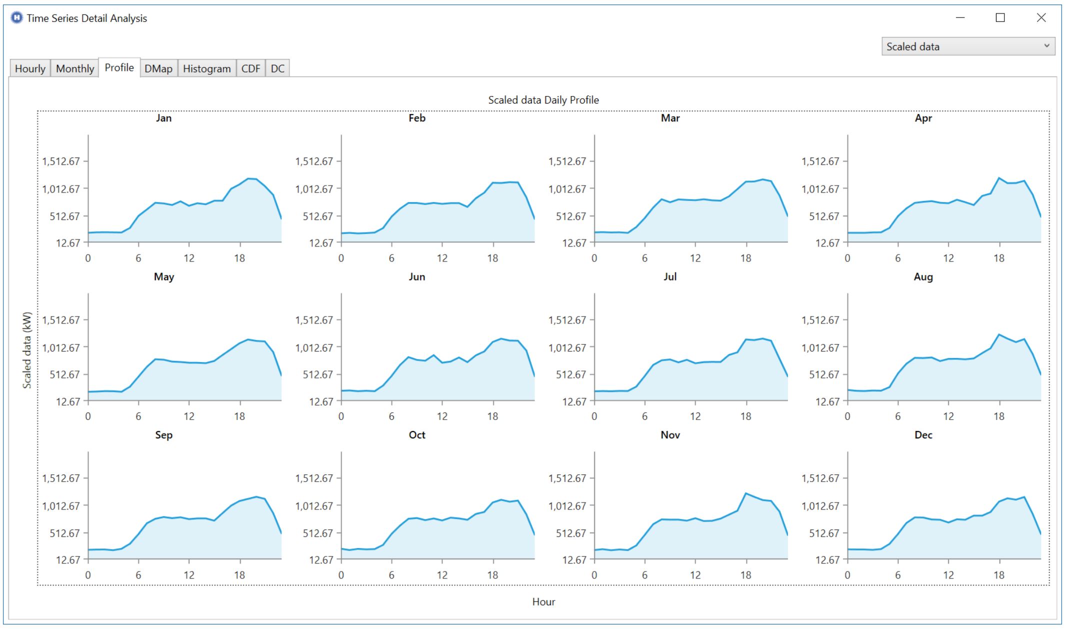


Figure 12: Estimation of Monthly Demand Profile

Thermal	**PV**	**Storage**
1625 kW	922 kW	Li-Ion: 833kW, 258 kWh

Table 4: Hybrid System Isabela

determining the best configuration of the system in economic terms. For this end, the cost of the biodiesel used in Isabela has been found to be €0.519/litre. Regarding the renewable energy production, it is of course highly dependant on the weather conditions. In Isabela there is no wind production, but the solar resource information is obtained directly from HOMER Pro. It is possible to specify the location of the system, and once fixed, the software downloads weather data from NASA Surface Meteorology and Solar Energy database. The rest of values have been left as in the default system, as we will see in subsection 4.2 when the system design in HOMER Pro is assessed.

4.2 System Design in HomerPro

4.2.1 Location

The first step towards modelling the system in HOMER Pro is establishing the location. This study, as we have already stated, is focused on the Isabela island, which belongs to the Galapagos archipelago, located west from Ecuador. The coordinates found in HOMER Pro are:

- 0°8.1' South
- 91°8.1' West

Figure 13 shows the user-interface with the home screen in HOMER Pro. In the top right corner we can determine the location. The top left corner shows an schematic of the system designed. As we can see, it is still not configured. After introducing all the components it will look as Figure 14 shows.

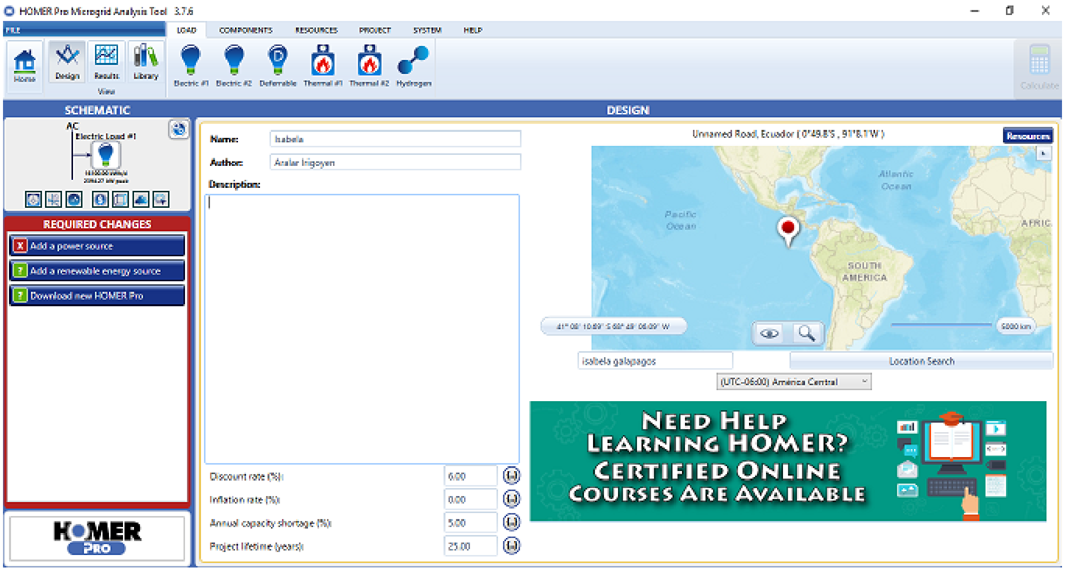


Figure 13: Home Screen HOMER Pro

For simplicity, it is considered a generator of 1625 kW instead of five generators

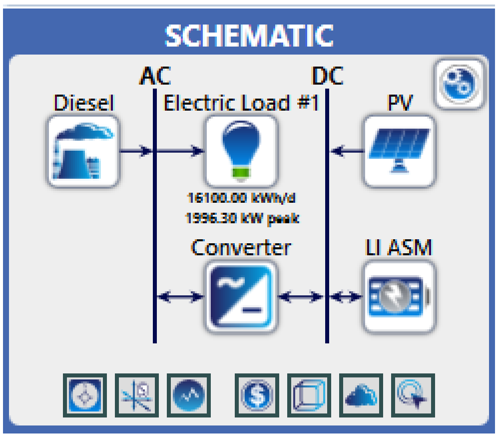


Figure 14: System Schematic

of 325 kW. This is the only generation component connected to the AC bus. The load is assumed to have only AC component, and the converter links the DC to the AC bus to convert the power from the PV array and the battery bank. In the case of the battery bank in can act as an rectifier also, when the surplus of energy generated due to the generator operating constraints is used to charge the batteries. On the other hand, the PV array and the battery are connected to the DC bus.
The configuration for each component and the load is explained below. We can use the toolbar showed in Figure 15 to access and add each component. This toolbar is accessed by clicking on the "component" tab in the home screen.

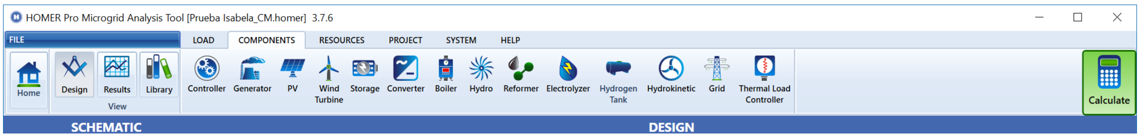


Figure 15: Component Toolbar

4.2.2 Load

Figure 16 shows the two screens where the load is configured. The first one appears after clicking on "Electric#1" in the Load tab, and in this step we define the profile of the load curve, in this case community because Isabela is neither a purely industrial nor residential region, as well as if there is a peak month, January for the case study. In the second screen we introduce the daily energy consumption to properly scale the load up, and we define the allowed day to day variation. The second screen is the interface where we can find various forms of representation of the demand, such as hourly, monthly and annual/hourly representations.

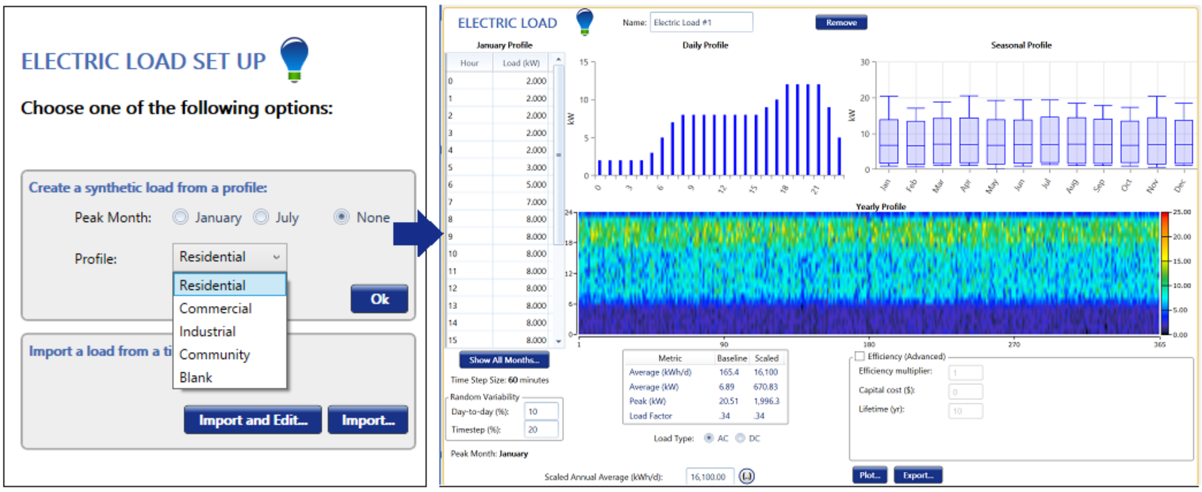


Figure 16: Load Settings

4.2.3 Diesel Generator

As it has already been mentioned, in order to simplify the model one generator of 1625 kW is considered instead of five 325 kW generators. Figure 17 shows that a generic generator was selected with a power capacity of 1625 kW. Other required inputs are fuel and its cost. We can find this in the bottom part. Diesel was selected and the price (€0.519/litre) was introduced. When we select the fuel the program automatically recovers information about it including its calorific value, and carbon and sulphur content.

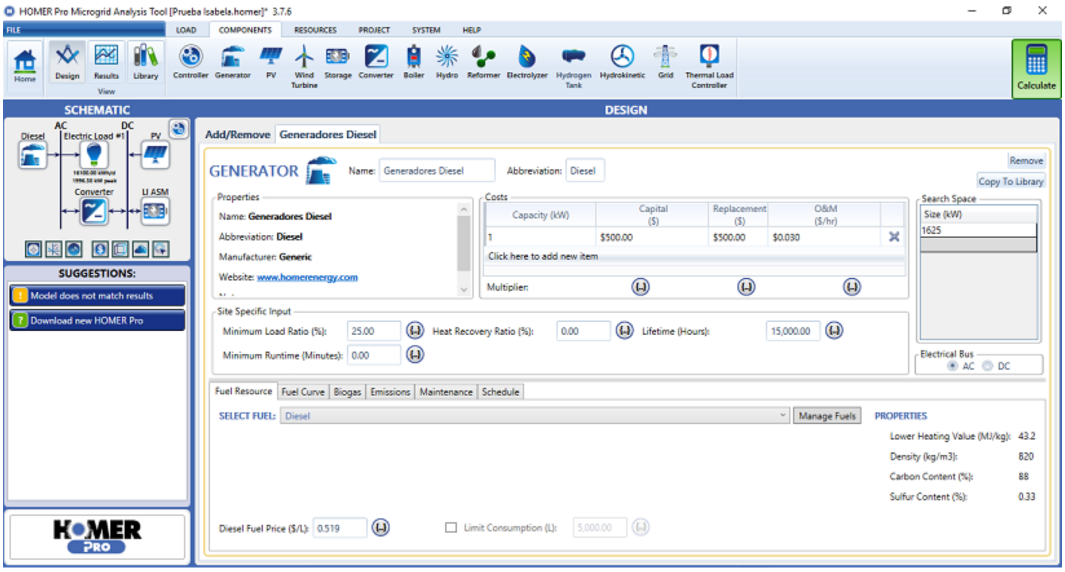


Figure 17: Generator Settings

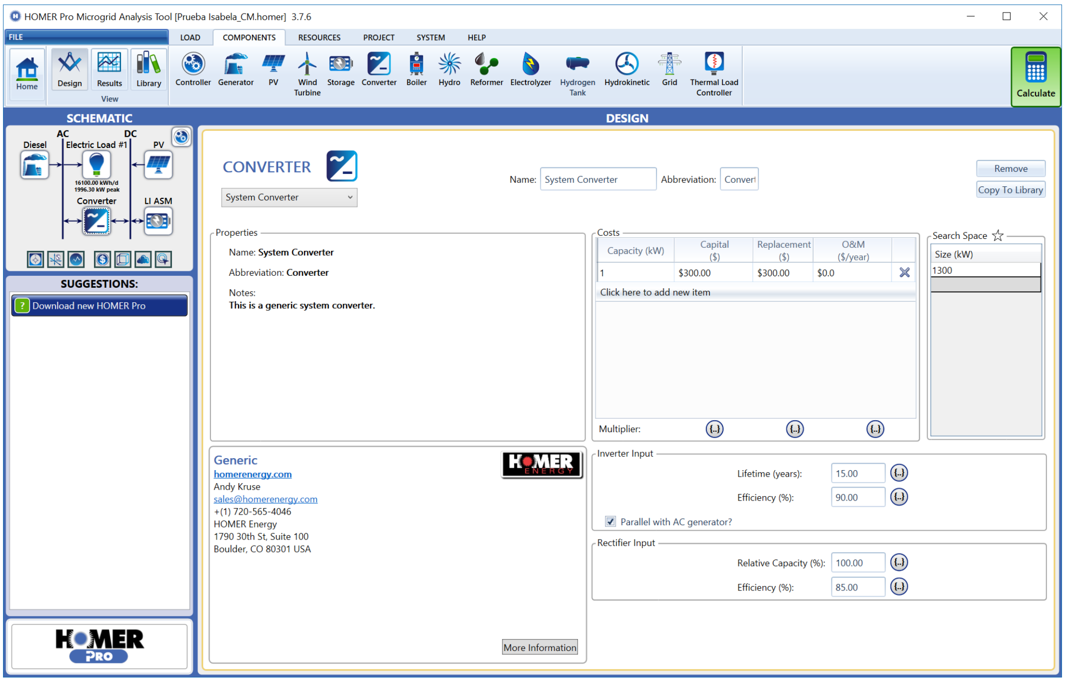


Figure 18: Converter Settings

4.2.4 Converter

Regarding the converter, a generic converter was selected, and all the default values were left, except the power capacity which was set to 1300 kW. This converter acts as the link between the DC and the AC bus, and it can function both in inverter and in rectifier mode.

4.2.5 PV Generation

In Figure 19 the setting for the PC array are shown. A generic flat plate collector was chosen from HOMER Pro library due to the absence of information about the model that will be installed in Isabela. The power has been set to 922 kW, the power of PV for the Hybrid System, as we can observe in the right upper corner of the image. Moreover it has been connected to the DC bus. The leftover variables have been left with their default value.

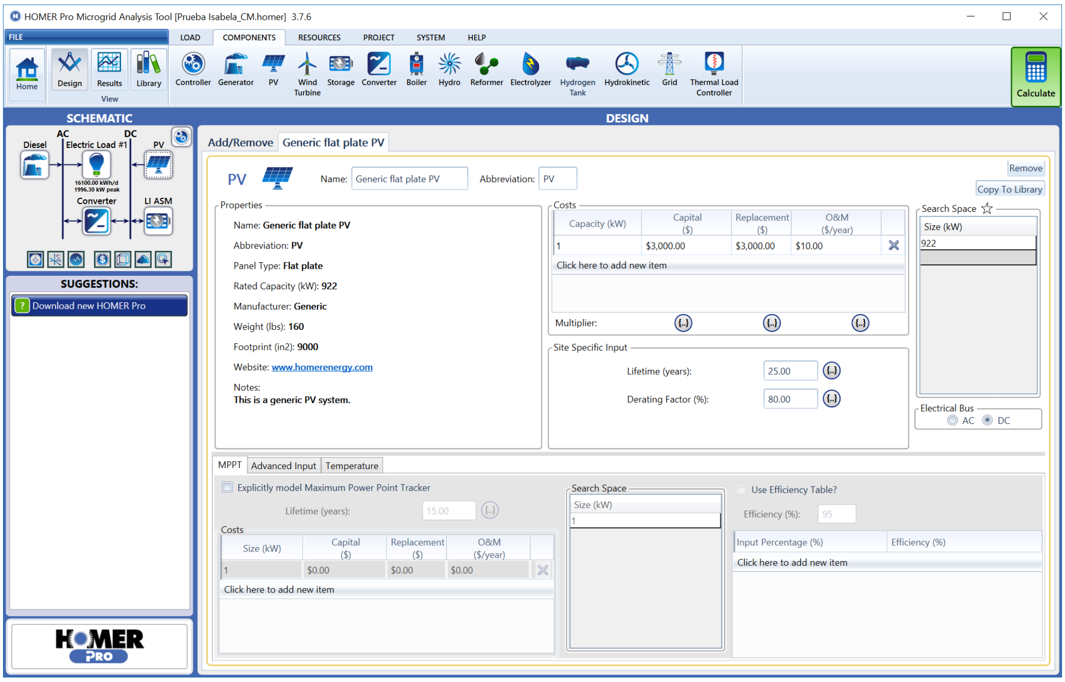


Figure 19: PV Settings

4.2.6 Battery Bank

The batteries installed in Isabela will be Li-Ion, with a total capacity of 258 kWh and a rated power of 833 kW. To add a battery bank first we need to select "Batteries" among the storage options and then search for the desired one in the software library. HOER Pro offers a wide range of storage options: Batteries, supercapacitors, flywheels and pumped hydro. Pumped hydro could also be a good option in some cases as a large storage option. However, as HOMER Pro is a software still in development not all the technologies are compatible with the MATLAB controller. Although this is irrelevant for our case study as the installed technologies do not present this problem, it is worth to point out that if we were interested in considering pumped hydro for instance, we should use another controller.
For this study, a generic battery was selected from the library, with some minor changes introduced. HOMER Pro allows us to modify the technical information of the components through the library interface. In this way, we can adapt the components to make them more similar to the ones we will use if the model we need is not already included in the library. The problem with the battery was that

the cycle lifetime was somehow outdated, so it was slightly modified to meet the models currently in the market. To do so, the Saft Li-Ion battery was taken as reference [45] . In Figure 20 we can see the user interface where the data of the selected storage option is displayed. All the technical information is on the left side. on the right we can introduce the desired rated energy and the costs, as well as specifying which bus the storage should be connected to, in this case DC.

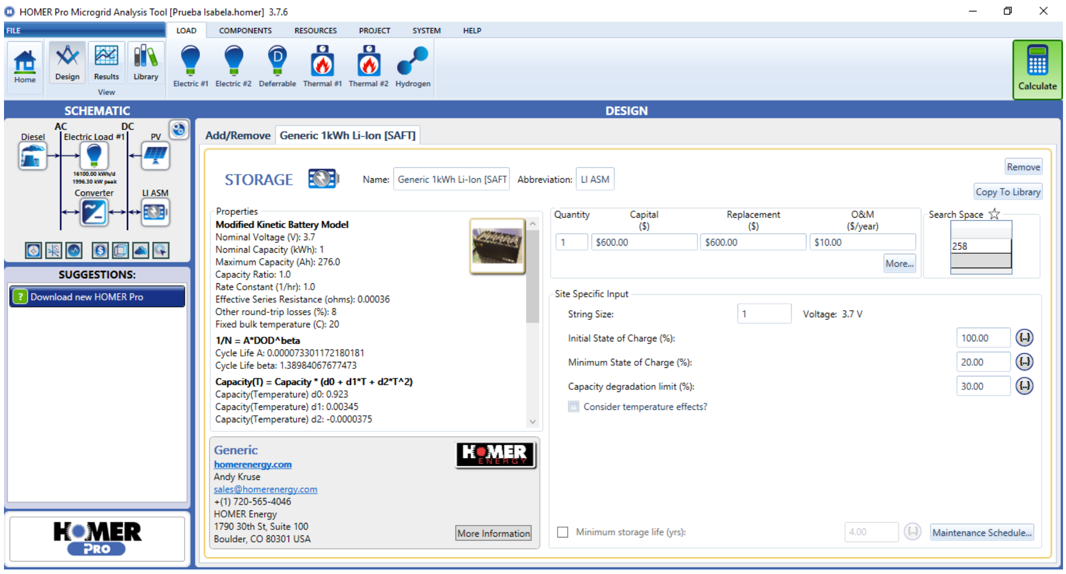


Figure 20: Battery Settings

4.2.7 Controller

The first step to configure the controller is to choose between the available ones. As it was explained in subsubsection 3.3.2, HOMER Pro offers four different controllers: Load Following, Cycle Charging, Generator Order and MATLAB Link. For the first three the energy management system is embedded in the program architecture, for the last is the used who has to define the strategy and how to implement it. Figure 21 shows the screen where the user must choose the controller from the drop-down menu. In the following sections the configuration for each controller will be explained.

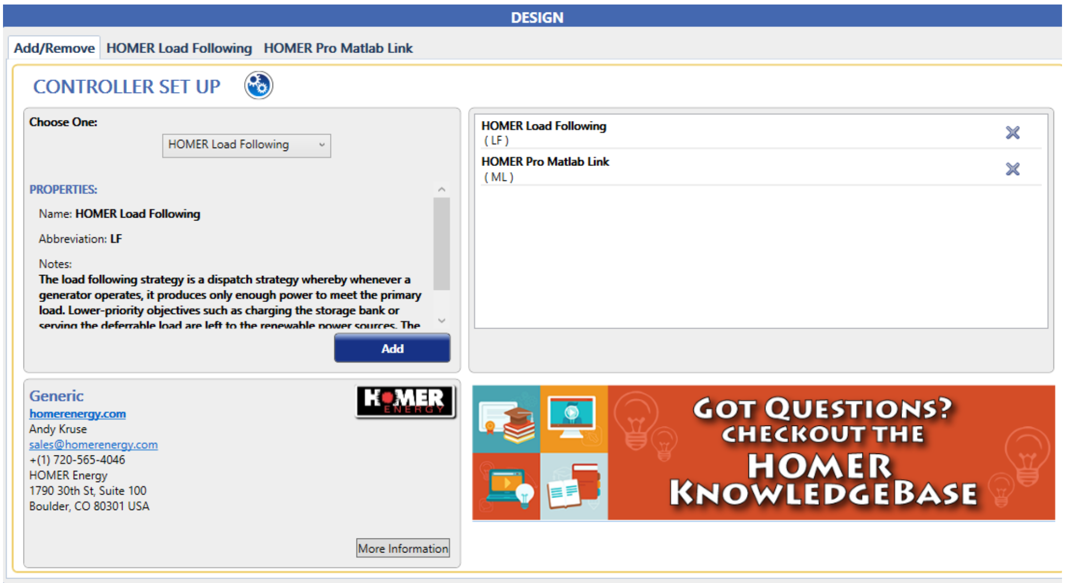


Figure 21: Controller Selection Screen

4.3 MATLAB EMS

As it was related in section 2.2, an energy management system is a control software that can optimally allocate the power output among the DG units and economically serve the load. In this case the EMS has been specifically designed to dispatch the energy generation in the isolated microgrid in Isabela, and serve the load.
The link between MATLAB and HOMER Pro is a new feature and it is still limited. There are many features of the software and even some components that could not be included in the EMS, including the prediction of the solar resource, and therefore the aim of the EMS is to optimize the dispatch to obtain the lowest cost.
When managing an electrical network one of the components that are essential in the dispatch strategy is the storage system. The current high cost of batteries, together with the environmental damage caused at the disposal of hazardous the materials of which the batteries are made justify the preference to prolong the batteries life as much as possible.
Due to the chemical kinetics involved, batteries cannot work during long periods of time at high power levels. Moreover, quick, deep, discharges can cause an early substitution of the battery as the heating created by such mode of operation shortens the battery lifetime.[46]
As batteries store DC charge, a converter is required at he interface with the AC system. Optimizing the converter design is also important when studying the batteries operation. This EMS prioritizes the charge of the batteries with energy from the PV collectors when it is possible to reduce the use of the rectifier and the consumption of fuel.
Overall the EMS strategy seeks to extend the batteries expected life while meeting the demand.In doing so, it considers that as the time steps in HOMER Pro are of one hour, that maximum power output will be 258 kW instead of 833 KW, taking into account that the energy capacity is 258 kWh.[47]
The algorithm first action is to check the state of charge of the batteries. The threshold value is 20% because this is the value defined in the CC MATLAB controller as well. Both if the state of charge is below or above this value, if the system can face the load with the PV generation alone it will do it, if this is not the case however, the behaviour will depend on the state of charge.
If the charge is below 20% it will try to avoid any further discharge and will try to charge them if it is possible.In this case if the generators have to operate they will do so at maximum power ad the excess energy will be used to charge the batteries. On the other hand, if the state of charge is above 20%, when the generators have to go into operation they will do so at minimum load, and the PV will be used as long as it is available. The batteries will only discharge when together they cannot meet the load. However, if the discharge required is at a very high power level the algorithm will increase the generator power instead. If there is excess electricity generated it will be used to charge the batteries as long as they are below 40% charge.
Last of all, the EMS defines the parameters HOMER Pro requires for the

simulations:

- Load Served
- Excess Electricity
- Unmet Load
- Operating Capacity Served
- Capacity Shortage

These are calculated once algorithm has dispatched the load between the different generation technologies and the set point of the batteries is defined.
The required functions, *MatlabStartSimulation, MatlabEndSimulation* and *MatlabDispatch* can be founf at the end of the document in the appendix.

4.4 Results

As it has already been stated one of the objectives of this study is to compare the results from three different controllers. This section will be divided in four parts: the first three will include the simulation results of the LF, CC and ML controllers in that order and the last one will include the discussion of these results.

4.4.1 Load Following (HomerPro)

Load following is a dispatch strategy by which if a generator has to operate it will only produce as much power as it is required to fulfil the demand. Other objectives, such as battery charging, are taken care of with the renewable production in the system. Under this strategy, HOMER dispatches the system's controllable sources as to serve the load with the total east cost, while still satisfying te operating reserve requirement. In other words, under this strategy the renewable resources are usually prioritized. [43]
For this case the controller has been configured as shown in page 48. All the default values were left. When the simulation is run the results window pops up. This

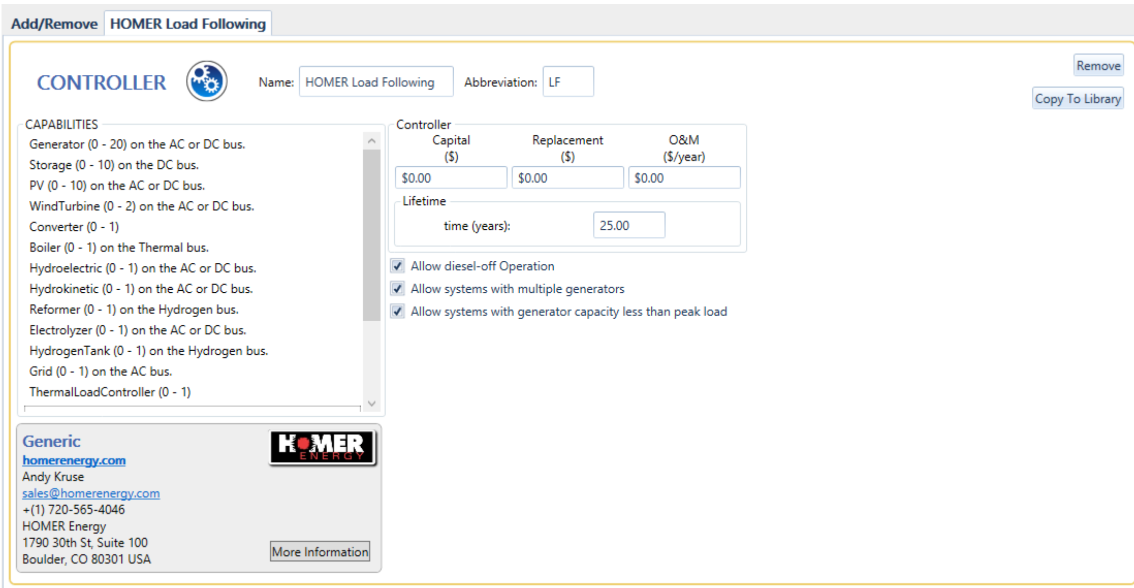


Figure 22: LF Controller

window presents all the possible configurations of the system that fit the strategy. It is particularly interesting when instead of introducing a fixed value for each generation component we introduce a range of values. In this case, HOMER Pro will provide a list of the possible sizing of the system that meet the load. However, as all the values we introduced were fixed the system comes up with a single solution. In Figure 23 we can see how the results are presented. The table header is divided in seven parts. The first, architecture presents the sizing of each component and the type of controller used. The second section presents a summary of the costs of the system: the cost of energy (COE), the NPC of the project, the initial capital required for the project and the operating cost. The third section, called system, includes the fraction of the load served by renewable sources. The four left sections are dedicated to each generation component and then converter. for each of them the program presents different characteristic variables such as costs, operating hours, production, amount of fuel consumed for the diesel generator, the batteries autonomy and the inverter and rectifier mean output. By clicking on

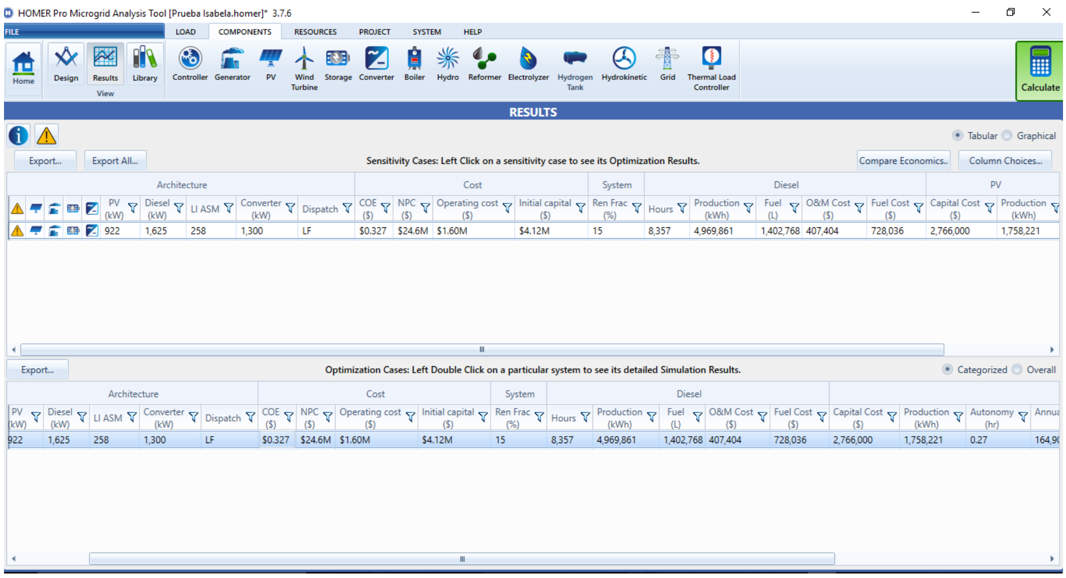


Figure 23: LF Results

each configuration (if there was more than one) we can access a great amount of information about costs, the operation of each component, time series, plots etc. The first window is a summary of the costs per component that can be seen in Figure 24

The cash flow is shown in Figure 25. As we can see the most of the periodic costs are due to the fuel consumption for the diesel generation. This costs are shown more extensively in Figure 26
The fuel usage is presented in monthly averages, daily and hourly. We can see that the fuel consumption is quite uniform throughout the year, concentrated in the period from 18 to 24h.

Similarly Figure 27 shows the usage of the diesel generators, the annual hours of operation, number of starts, and production, among other variables.

Although the renewable resources have also been used, the load is much higher, and the renewable penetration is only about 31% as showed in Figure 28. The renewable penetration takes into account not only the solar production but also the energy obtained from the batteries discharge, which is not necessarily renewable as they might have been charged by the generator. With only 922 kW of solar energy installed the island is still far from achieving the 100% renewable energy penetration goal that is set for the Galapagos archipelago and becoming indepen-

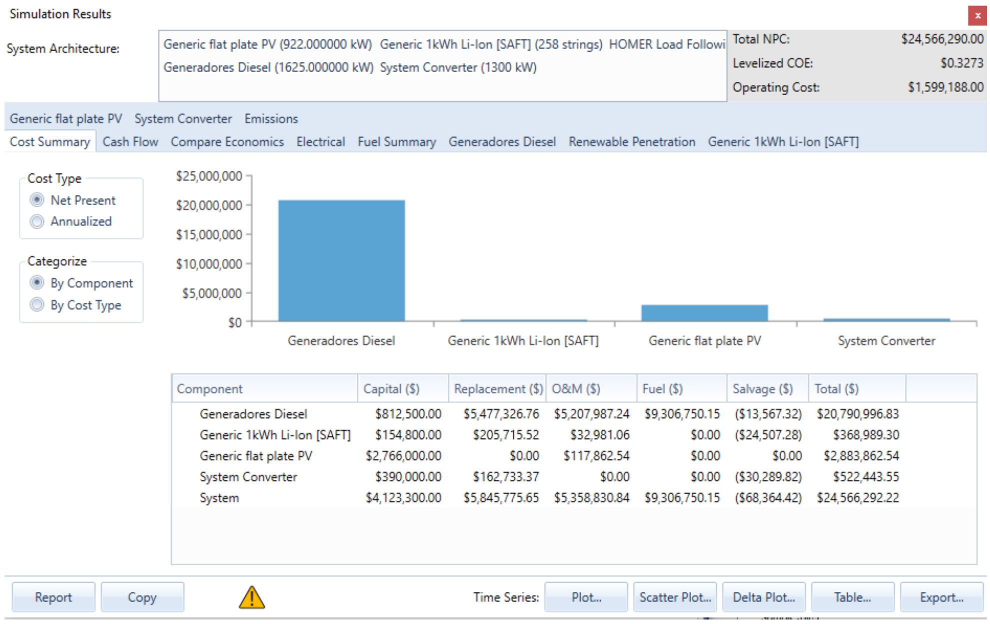


Figure 24: LF Costs Summary

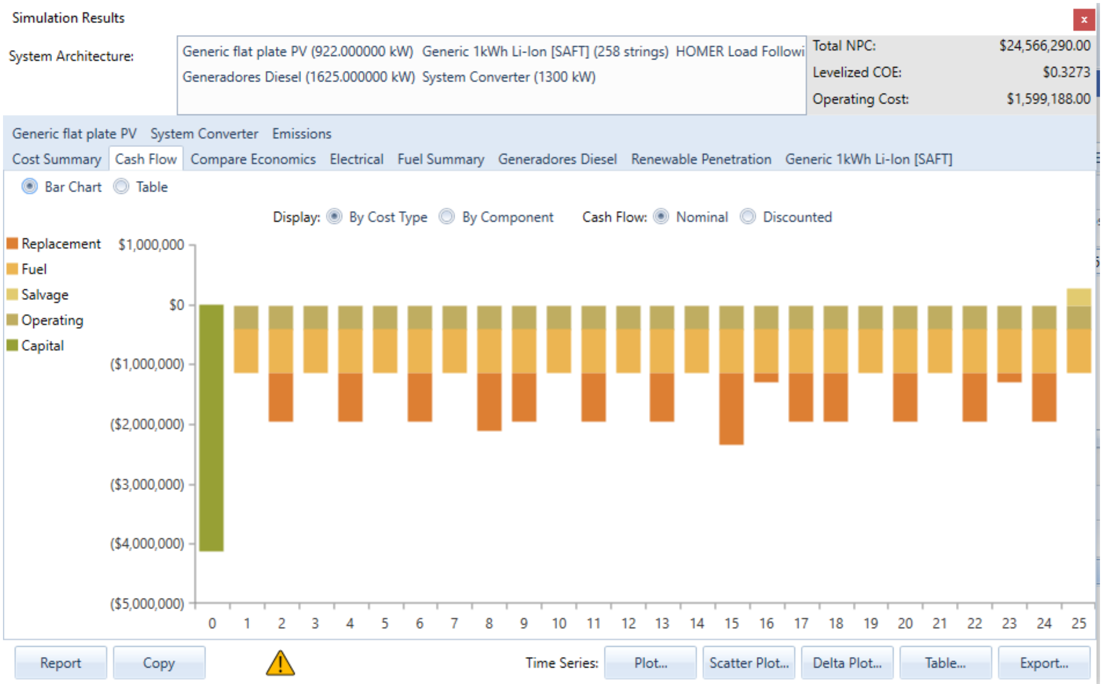


Figure 25: LF Cash Flow

dent from fossil fuels. The installation of additional renewable capacity will be required to meet this end.

Figure 29 indicates that PV is generating at a low capacity factor, only 21.7%. In fact the mean output is 200 kW. On the other hand, it works 4380 hours per year, which means that it is in operation most of the daylight hours.

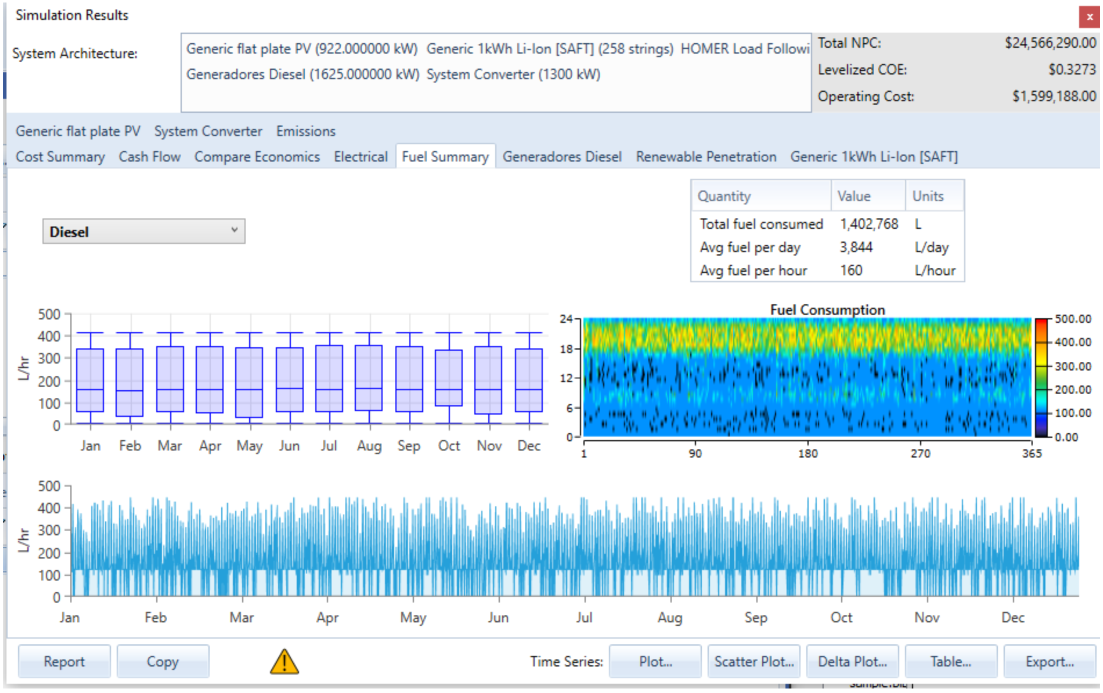


Figure 26: LF Fuel Usage

Figure 27: LF Diesel Generators Operation

The batteries are used during the peak periods to complement the rest of the production and meet the demand. The rest of the periods they are either charging or at full charge. When they are used they achieve approximately a state of charge of 20%. They do not discharge below this point to prolong the life expectancy of the batteries and minimize the wear cost per kWh.
From the graph on the bottom right graph in Figure 30 we can see that the state

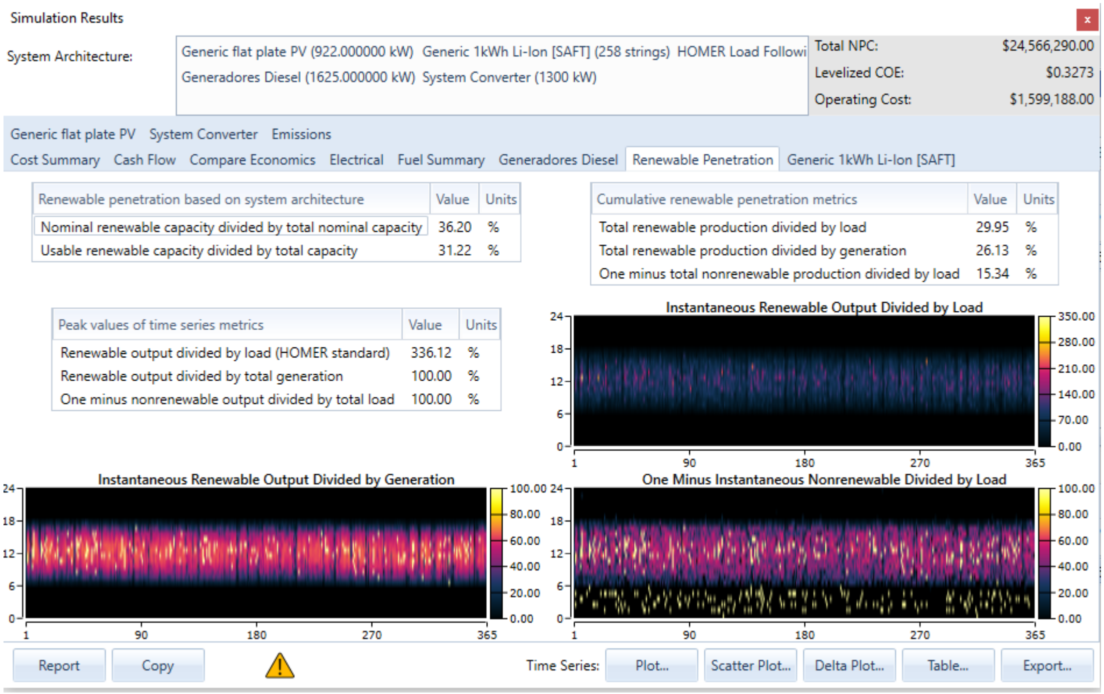


Figure 28: LF Renewable Energy Penetration

Figure 29: LF PV

state of charge during the year is between 20% and 100% every month. The average value stays constant a little bit above 60% for most months, with the exception of June and August when it is slightly lower. Also, from the top left graph we can extract that most of around 40% of the time the state of charge is 22.54 and 43%

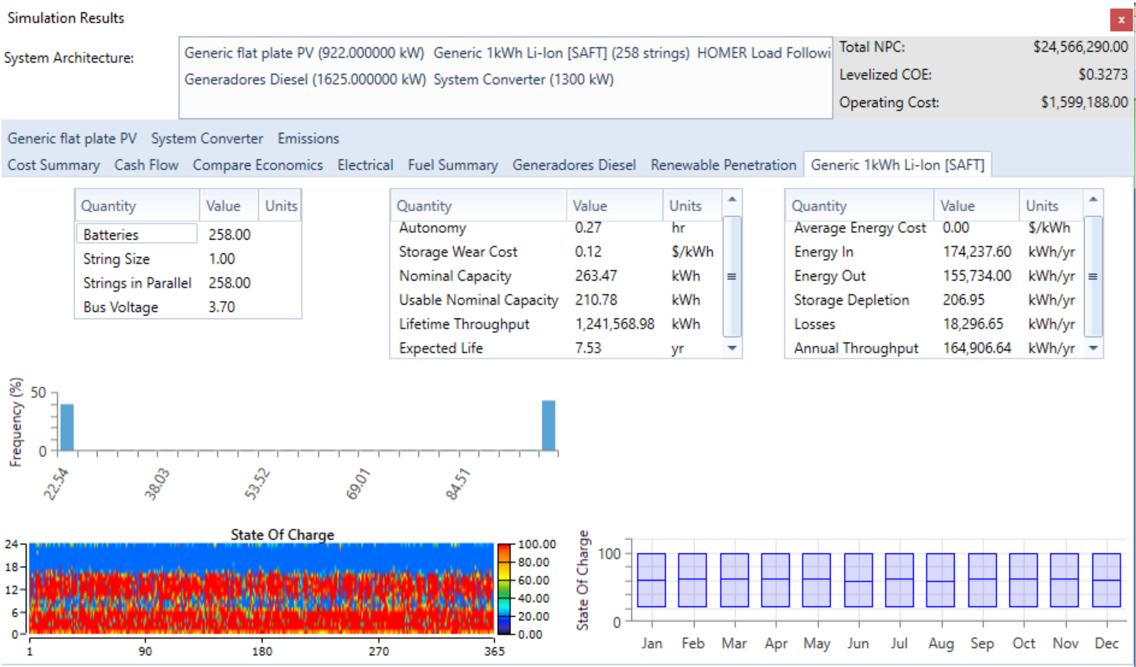


Figure 30: LF Battery Bank

of the time 100%. This means that only about 20% of the time the batteries are being used.

The converter works both as inverter and as rectifier. Figure 31 displays the

Figure 31: LF Converter

results of its operation. We can appreciate that the inverter function is employed more extensively both during the day and during the year. It works as an inverter when the demand is being partially or totally satisfied with PV power or with power from the battery bank discharge. For this reason, the inverter operated mainly during the daylight hours. The rectifier operates only when the power surplus from the diesel generator is used to charge the battery bank. We can see that the rectifying function takes place only during the off-peak period of the island, between 00:00 AM and 6:00 AM.

Quantity	Value	Units
Carbon Dioxide	3,693,949.55	kg/yr
Carbon Monoxide	9,117.99	kg/yr
Unburned Hydrocarbons	1,009.99	kg/yr
Particulate Matter	687.36	kg/yr
Sulfur Dioxide	7,418.09	kg/yr
Nitrogen Oxides	81,360.54	kg/yr

Figure 32: Emissions with LF Controller

Figure 32 presents the emissions resulting from the system. This will be used later to make analyse how the choice of the controller affects the environmental impact.

In the next pages the hourly load and generation schedule for a week are presented to study how the systems meets the demand. The selected dates have been from the 1^{st} to the 7^{th} of January. This dates will remain the same for the following controllers for the sake of making a fair comparison.

Figure 33 shows the load demand during the first week of the year. There is no

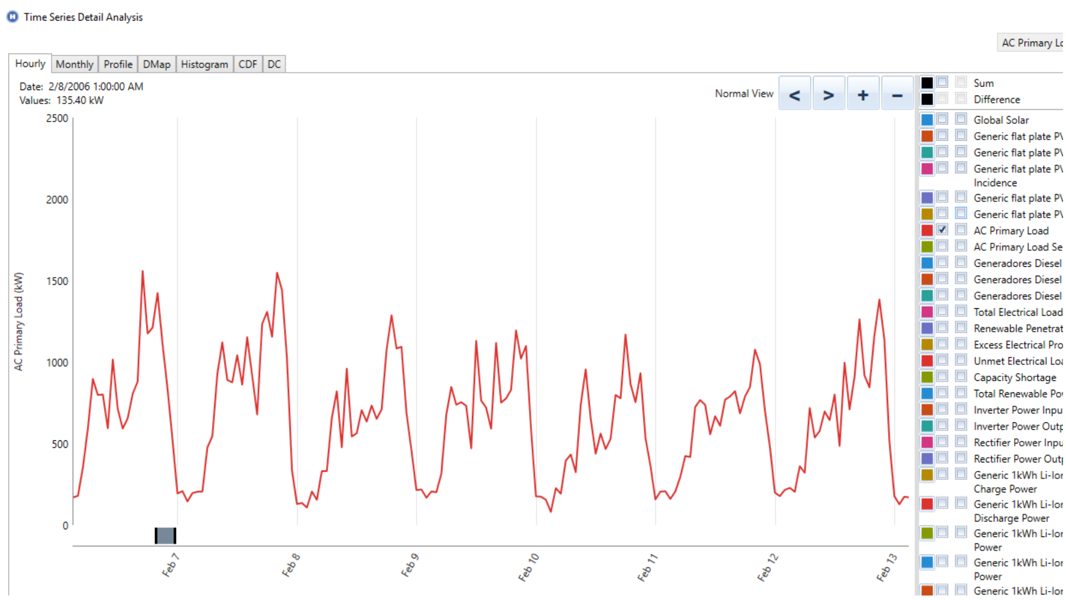


Figure 33: LF Primary Load on the AC bus (kW)

load considered on the DC bus, therefore this is the total demand the system has

to confront.
Figure 34, Figure 35 and Figure 36 show, respectively, the generation from the diesel generator, the PV system and the battery discharge.

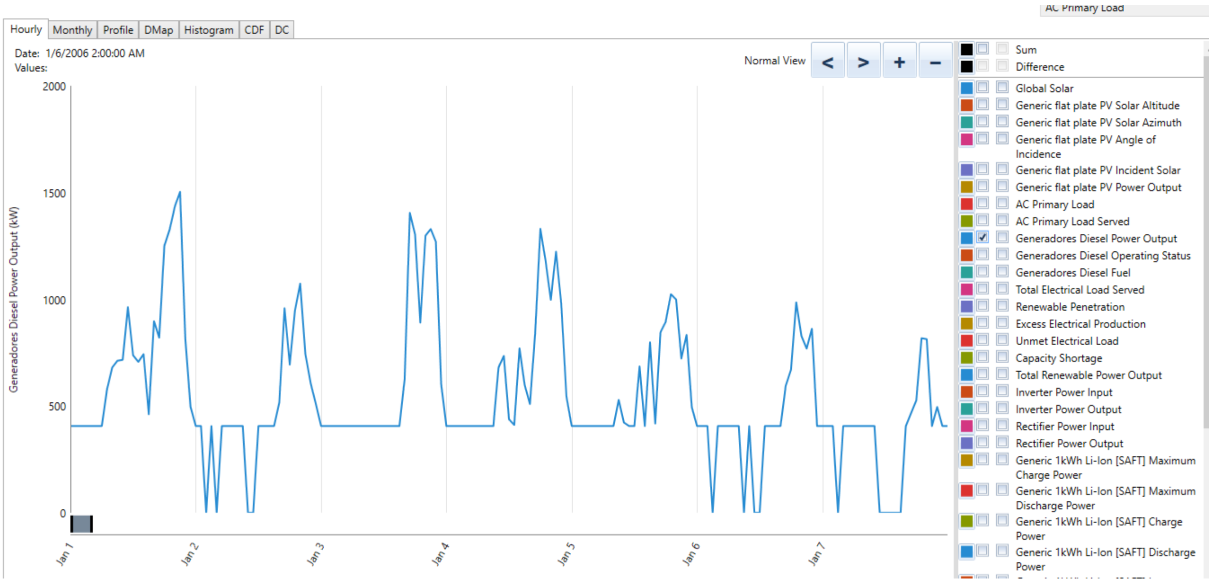


Figure 34: LF Generator Output(kW)

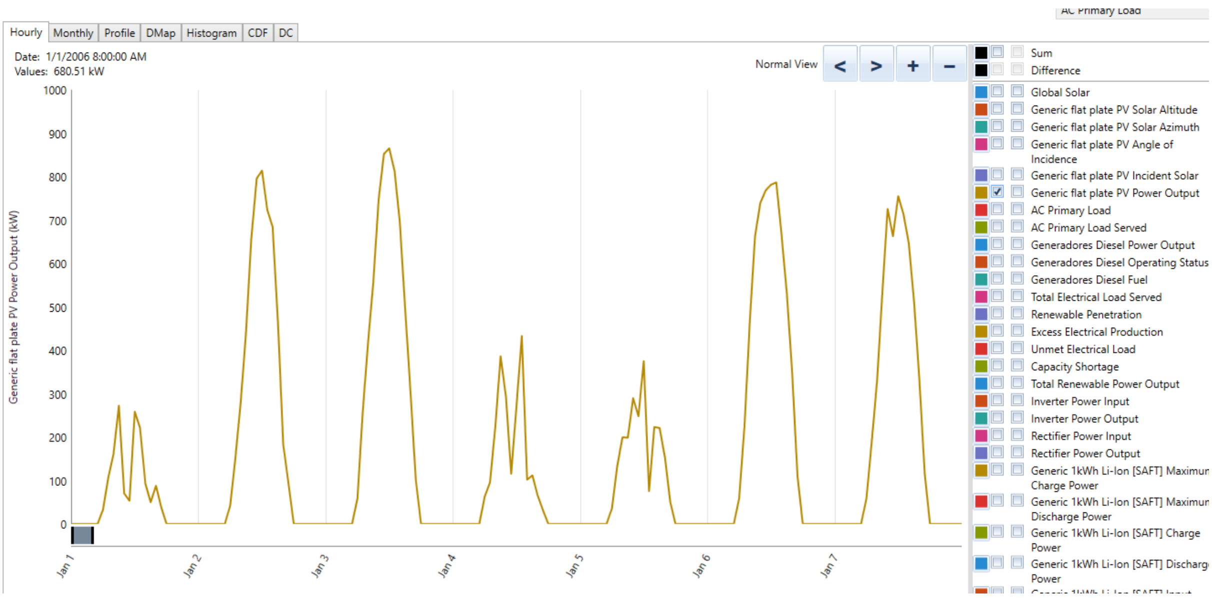


Figure 35: LF PV Output(kW)

Figure 37 shows all the previous in the same figure, to allow a better comparison.

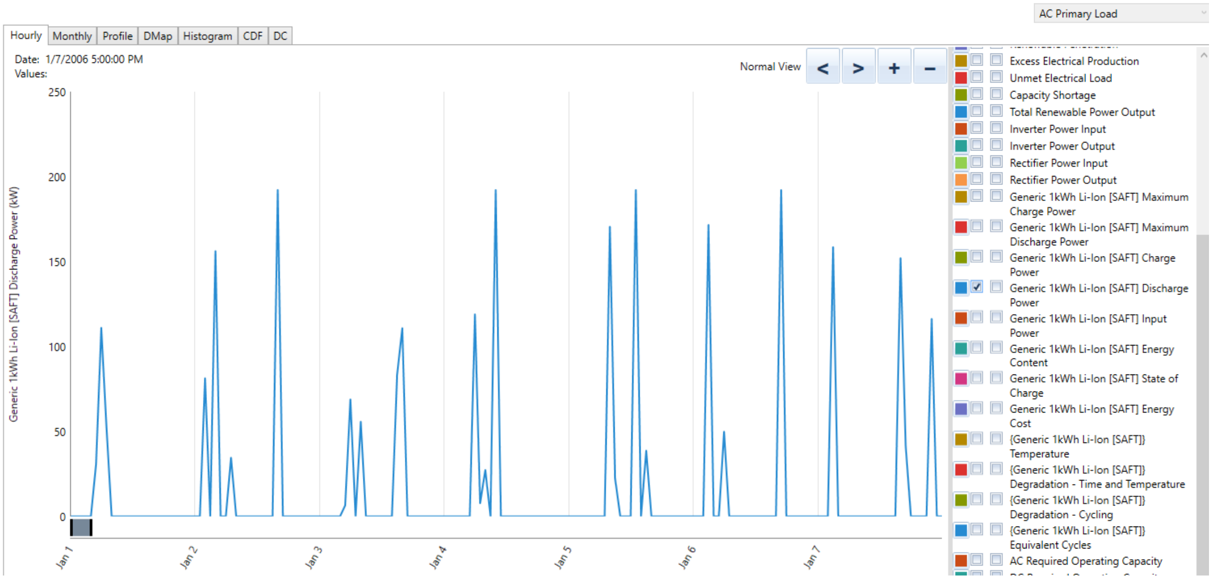


Figure 36: LF Battery Discharge (kW)

The load is represented in the lower graph whereas the upper one shown all the generation. It can be appreciated that batteries (blue line) only discharge occasionally during the day, usually twice as discussed before, and that they provide a small fraction of the total demand.

Figure 37: LF Load vs Generation

The battery bank operation schedule will be one of the factor that will change more depending on the choice of the controllers. For this reason Figure 38,Figure 39, and Figure 40 show the state of charge, and the discharge against the charge power flow and the last two against the total generation. These define the behaviour of the system regarding storage use.

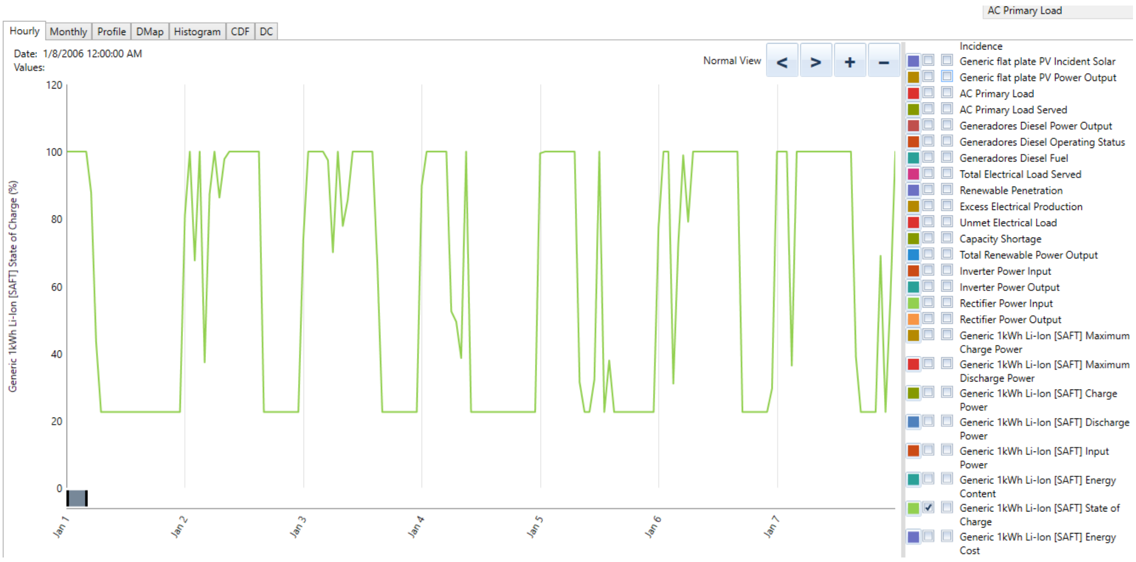


Figure 38: LF Batteries State of Charge (%)

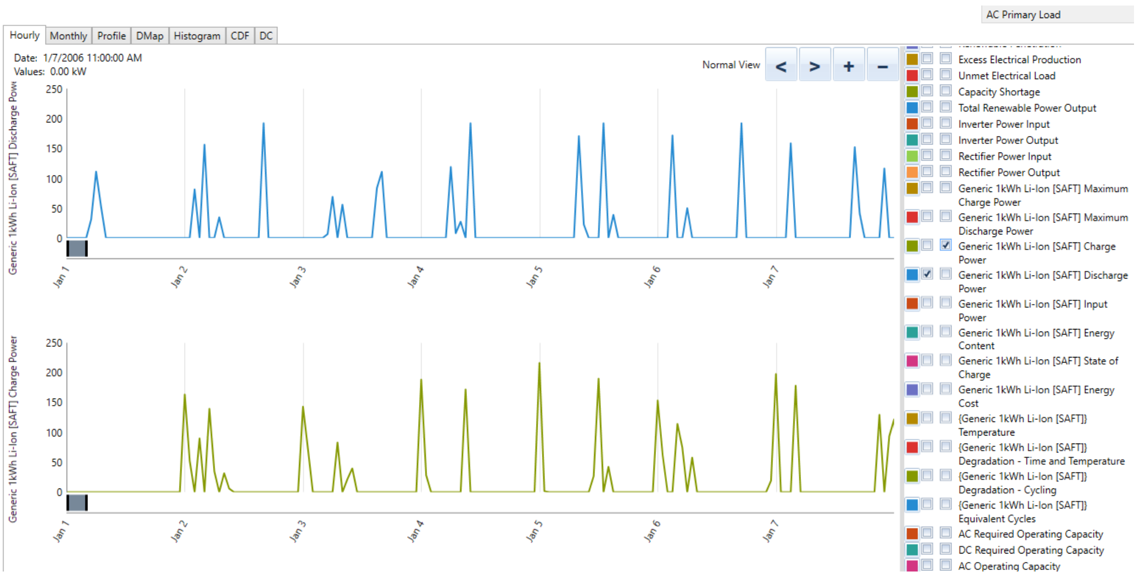


Figure 39: LF Battery Charge vs Discharge (kW)

Last, Figure 41 shows the renewable generation against the total supply.

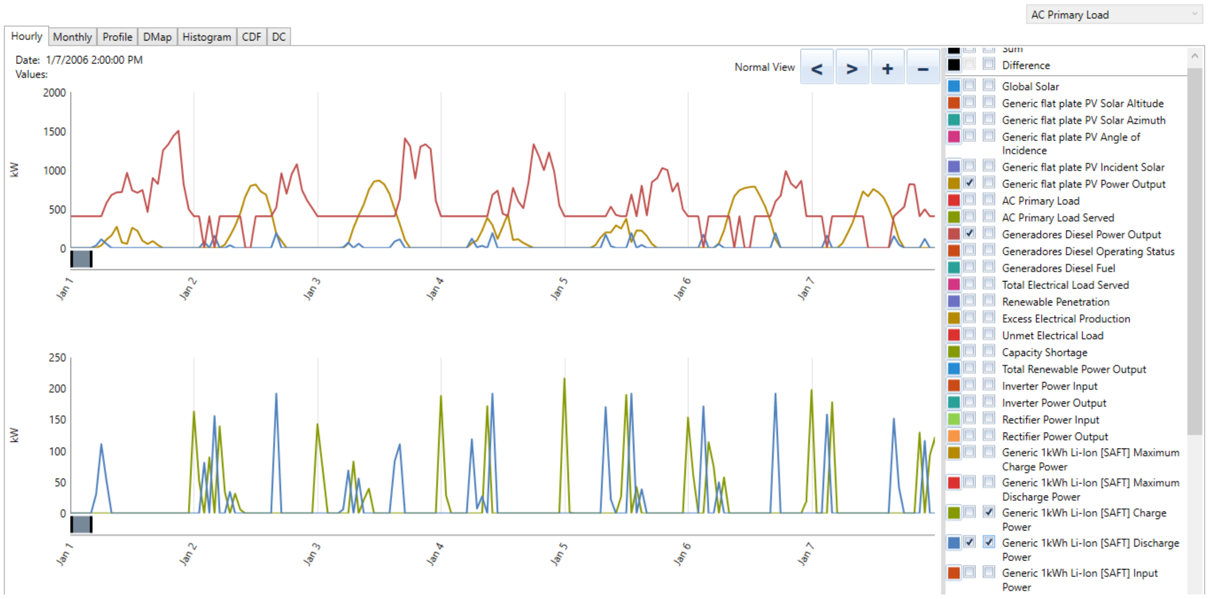


Figure 40: LF Charge/Discharge of the Batteries vs Generation (kW)

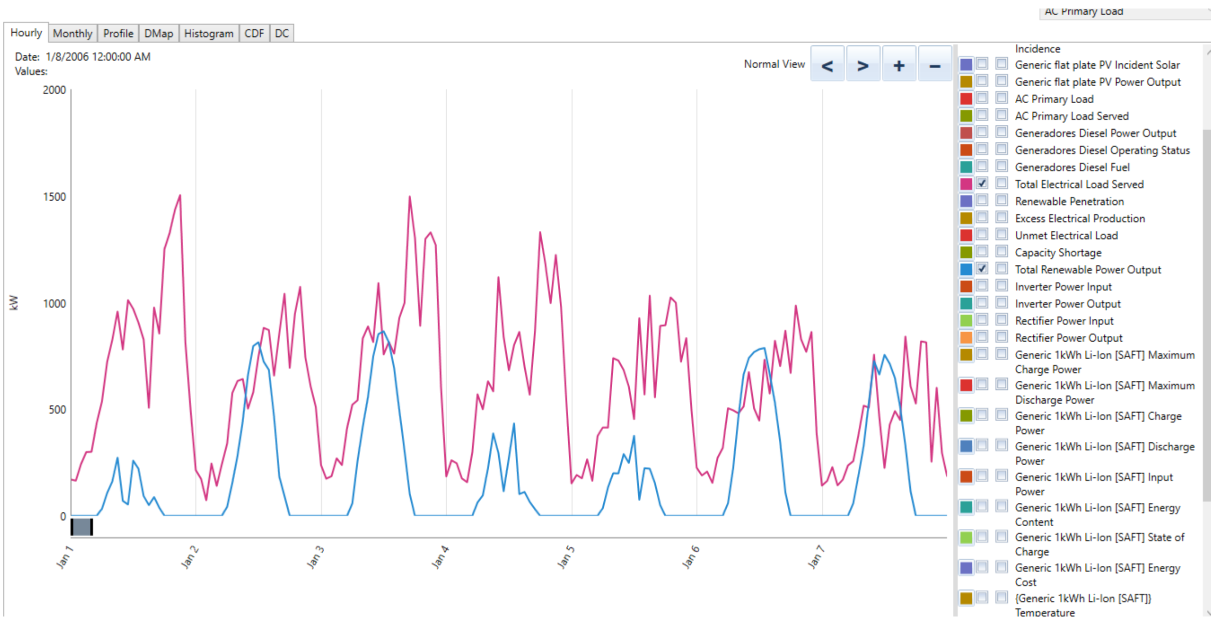


Figure 41: LF Renewable Generation against Load Served (kW)

To sum up, Figure 42 shows the monthly electrical production of the system.

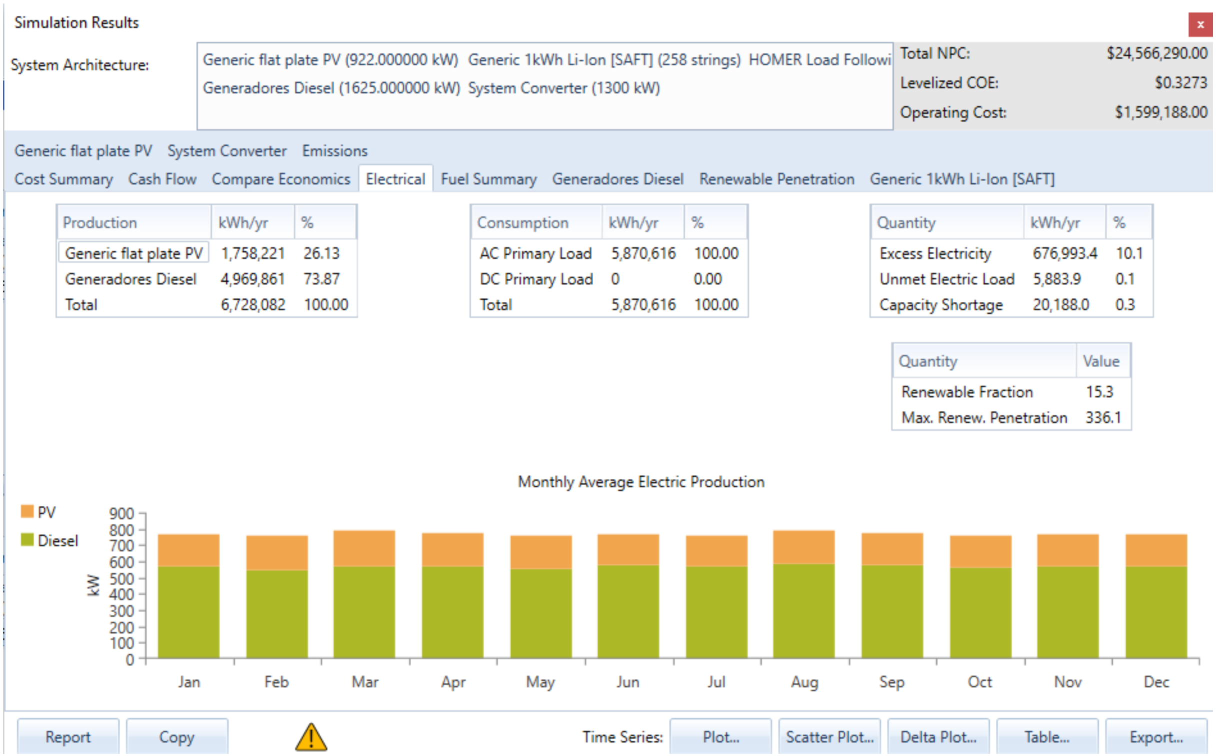


Figure 42: LF Summary of Monthly Production

4.4.2 Cycle Charging (HomerPro)

Cycle charging is a dispatch strategy by which if a generator is needed to go into operation it will do so at full power. The excess of electricity production will cover other lower priority objectives such as meeting the deferrable load, or charging the storage devices.
Under this strategy HOMER first dispatched the controllable loads in such a way that the optimal combination of power sources is sought in terms of minimizing the cost while meeting the load demand and the reserve requirements. Then, HOMER ramps up the operation of each generator to its nominal capacity or as close as possible without producing excess electricity. Moreover, if a set-point state of charge is has been defined for this strategy, when the state of charge of the batteries is below this predefined set point and thy were not not discharging in the previous time step, HOMER will avoid the discharge in the next time step. Also, once the system starts to charge the storage bank it will continue charging until it reaches the set-point state of charge again. What this strategy ensures is a higher state of charge of the batteries and continuous charge of the storage system.[43]
In the following pages, the same figures as in the previous section will be presented but in this case using the Cycle Charging controller instead of Load Following. The biggest difference lies in the operating cost and in the batteries lifetime, since this strategy aims to maximize their life expectancy, but to do so the generator production will increase resulting in more fuel consumption.
Figure 43 shows the controller for the cycle charge option. All the default values were left, including the set-point state of charge at 80%.

Figure 44 shows the possible configurations of the system. Again there is only one, but the production variables and the costs are different with respect to the previous case.
Below each of them will be analysed.

A summary of the costs for each component is provided in Figure 45, ad below them a table displays the costs for each of them in depth. The fuel cost increases significantly with respect to the LF case, but the total NPC remains quite constant.

In Figure 46 the cash flow of this case can be found, and as we can see the replacement cash flows are less frequent than with LF. The reason for this is the prolonged life of the batteries.
As it has already been mentioned the diesel generators have been used more than in the previous case, and as a consequence the fuel consumption also rises. The simulation results for both the generator operation schedule and the fuel consumption can be found in page 63 and Figure 48 respectively.

Although the generator is in operation less hours, it generates more power, but has to go through a higher number of starts.
Figure 49 shows the operational data from the PV collectors. It remains the same

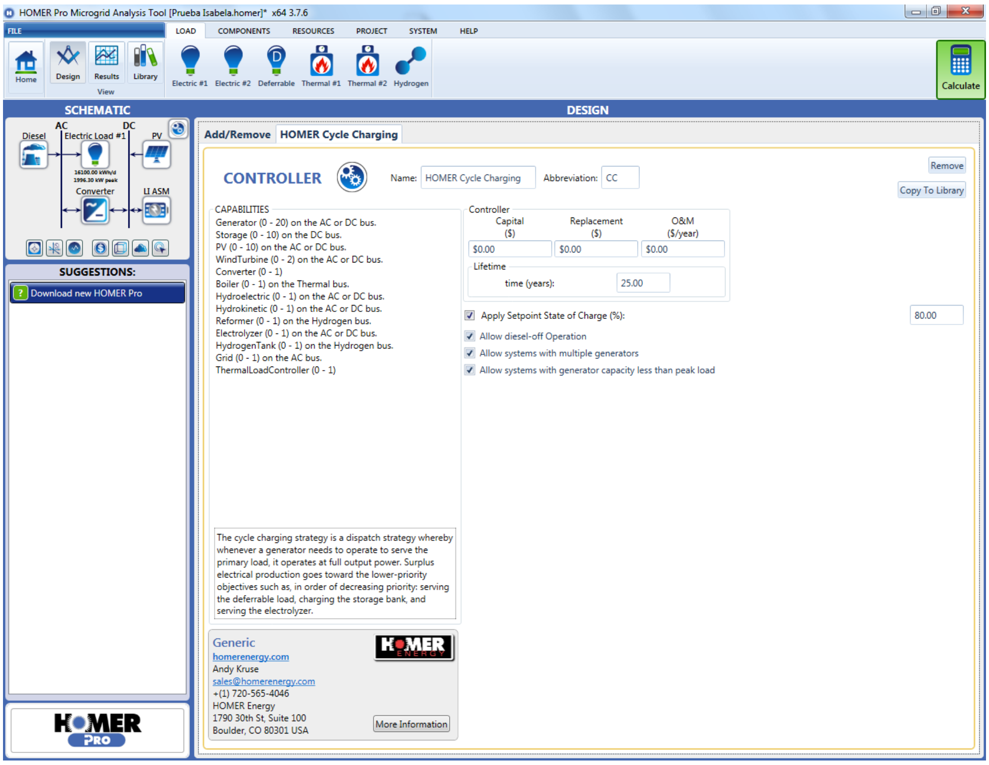


Figure 43: CC Controller

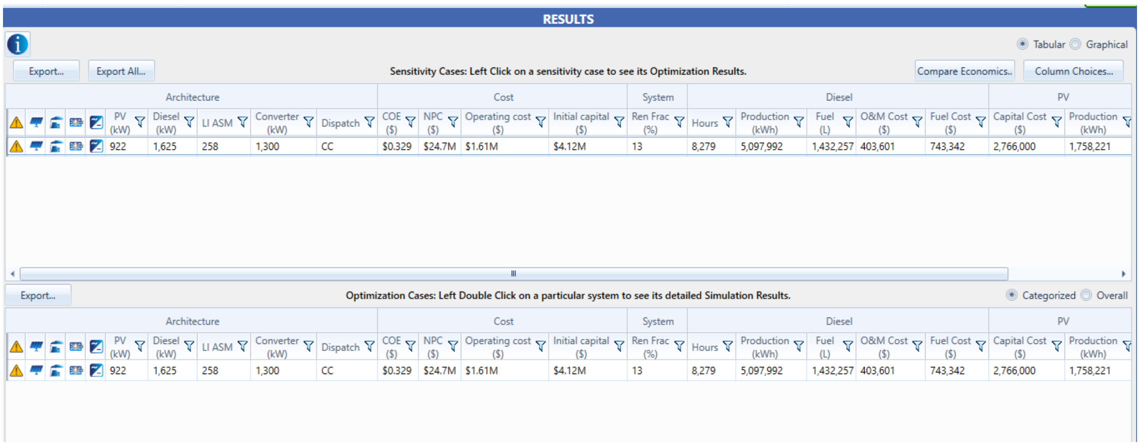


Figure 44: CC Results

as for the previous case, with a mean output of 200.7 kW and a capacity factor of 21.77%.

The figures below, Figure 50 and Figure 51 show the simulation results for the batteries and the converter

As it can be appreciated the batteries present a very different behaviour with respect to the load following strategy. Their state of charge remains above 80 % for most of the day, all the days of the year. In fact, as seen in the graph on the bottom right of Figure 50, the state of charges is between 50 ab 100% during most months, with an average value well above 80%, and in some cases close to 100%,

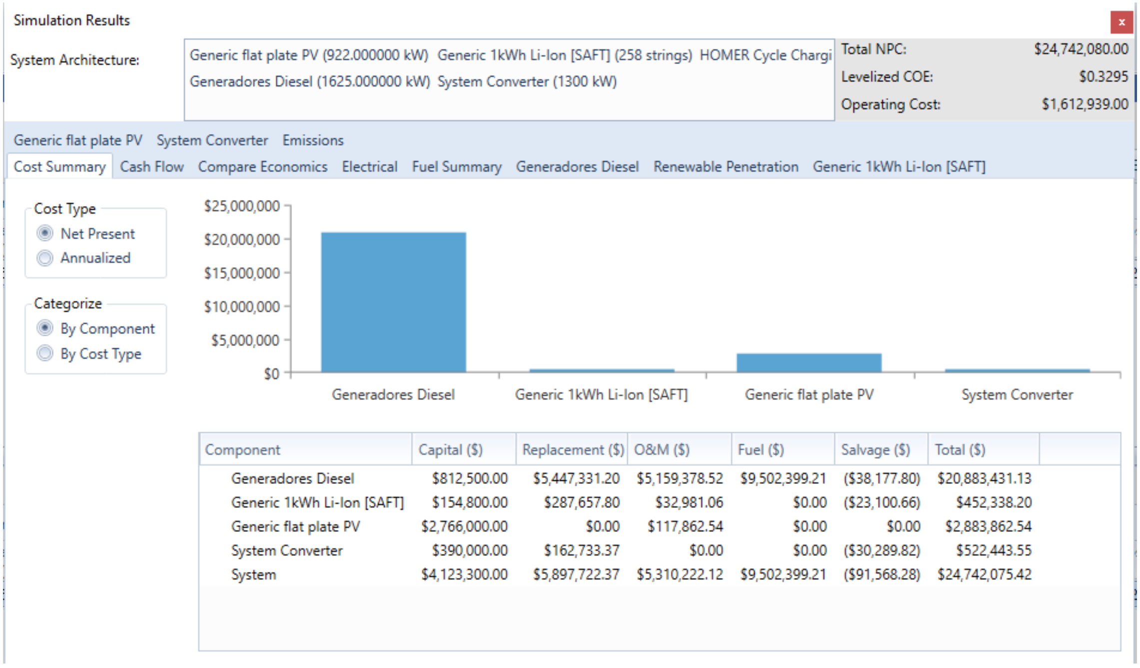


Figure 45: CC Costs Summary

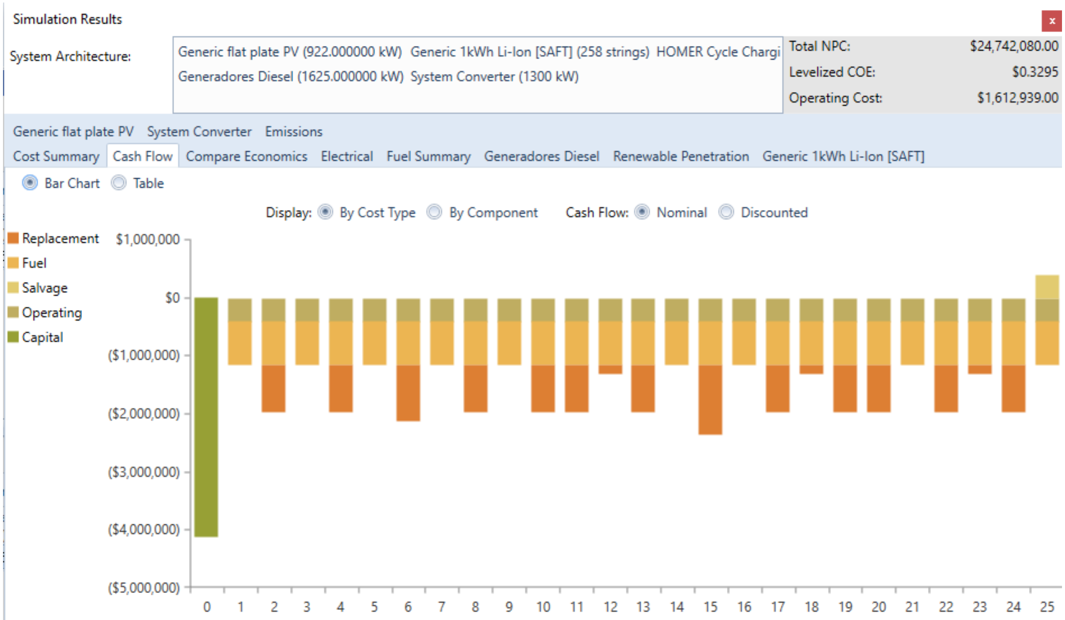


Figure 46: CC Cash Flow

as is the case of October that as we can recall from Figure 11 is the month with lowest demand. Figure 51 shows the converter results. Again the inverting function is used more extensively to integrate solar power, and the rectifying mode, used to charge the batteries with the left over power from the generator is used from 6pm to 6am but not during the day, when solar power can perform this task as well. With respect to the load following strategy the rectifier use increases, and the capacity factor rises from 0.91% to 1.41%.

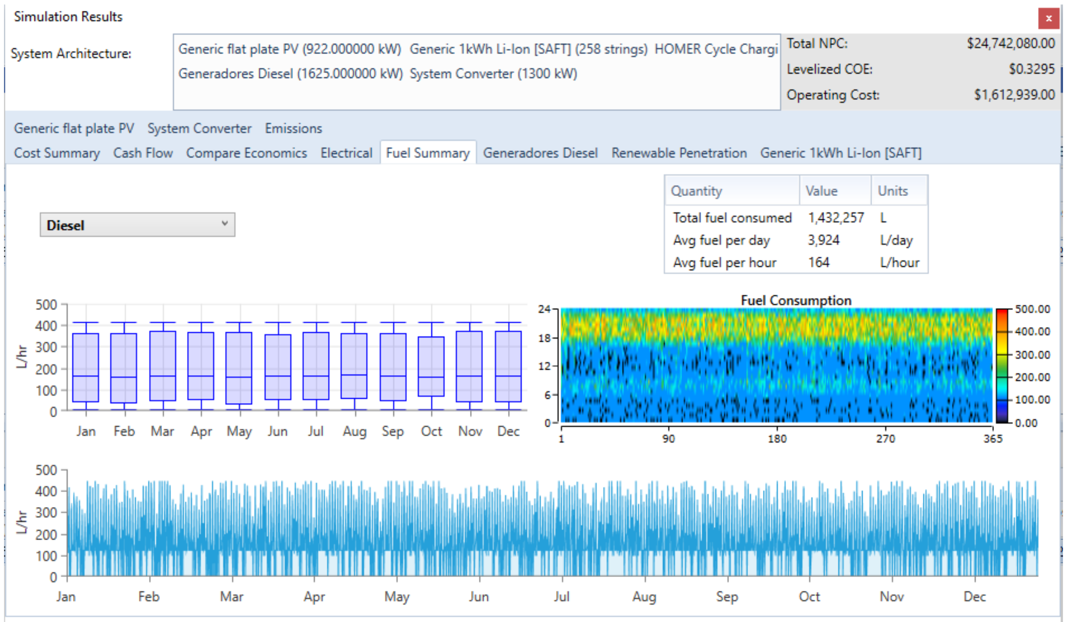


Figure 47: CC Fuel Usage

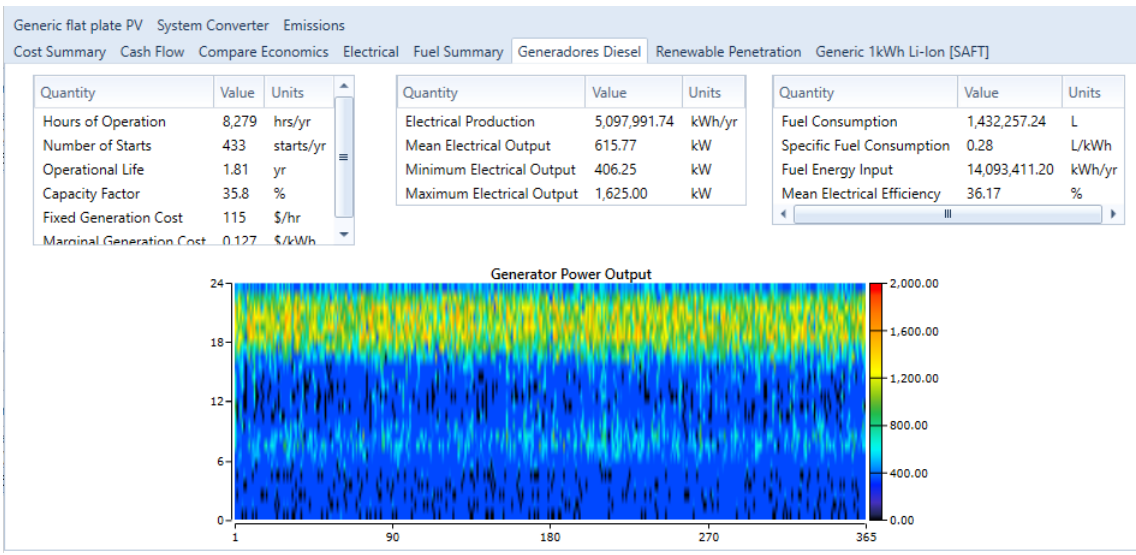


Figure 48: CC Diesel Generator Operation

Last, the total renewable penetration results are presented in Figure 52. Let's recall that this results include the production not only for the solar PV collectors but also from the batteries. Overall the renewable penetration achieved is very similar with a value of 36.2%. The dispatch schedule simulated results in the emissions shown in Figure 53. As a consequence of a larger use of the generator they also increase with respect to the LF case.

Below, the results of the dispatch schedule will be presented. As before, the period from the 1^{st} to the 7^{th} of January has been selected to enable the comparison of the results from all the cases.

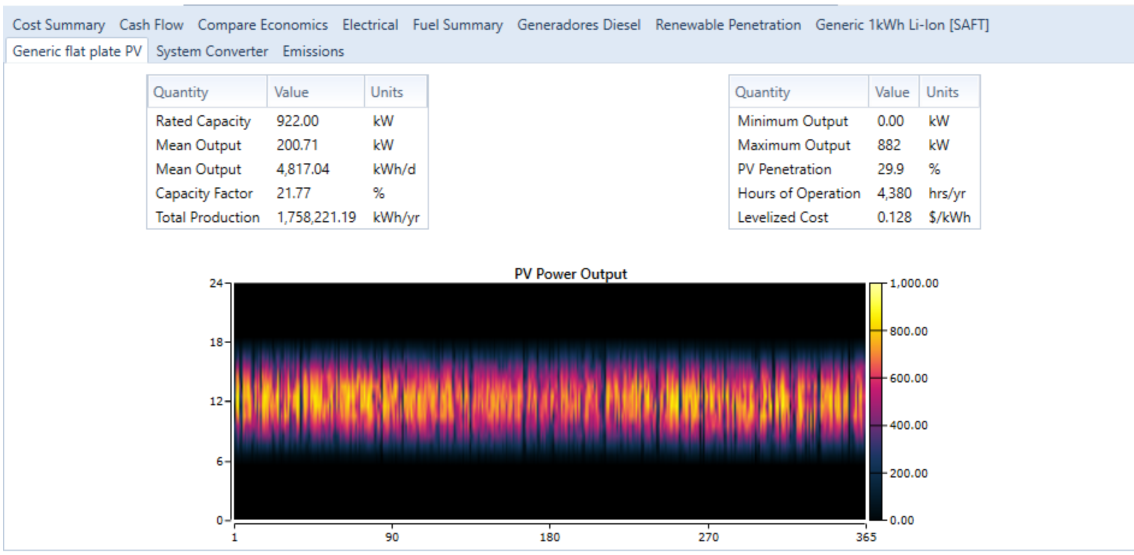


Figure 49: CC PV

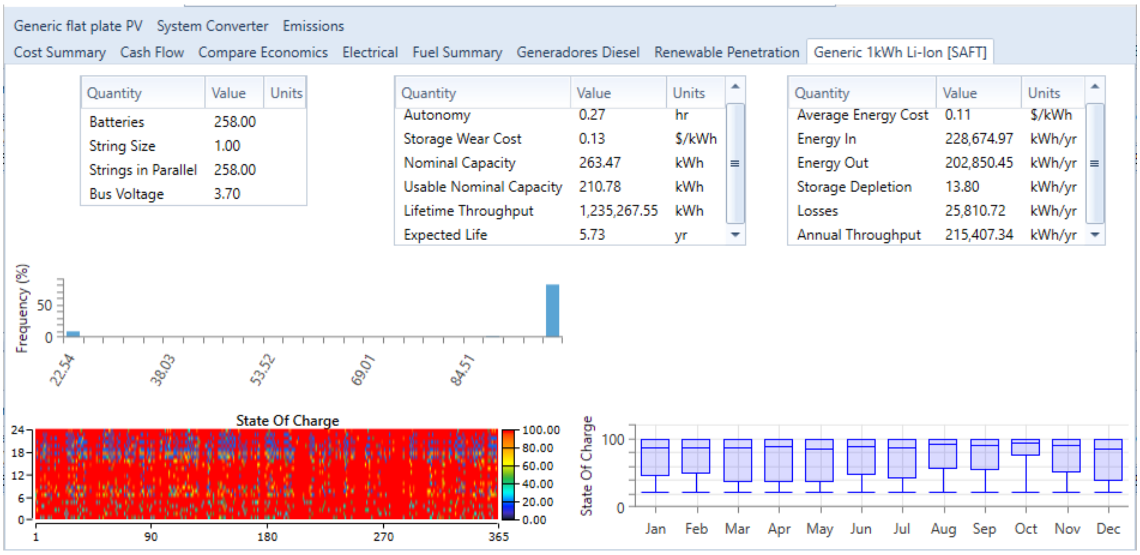
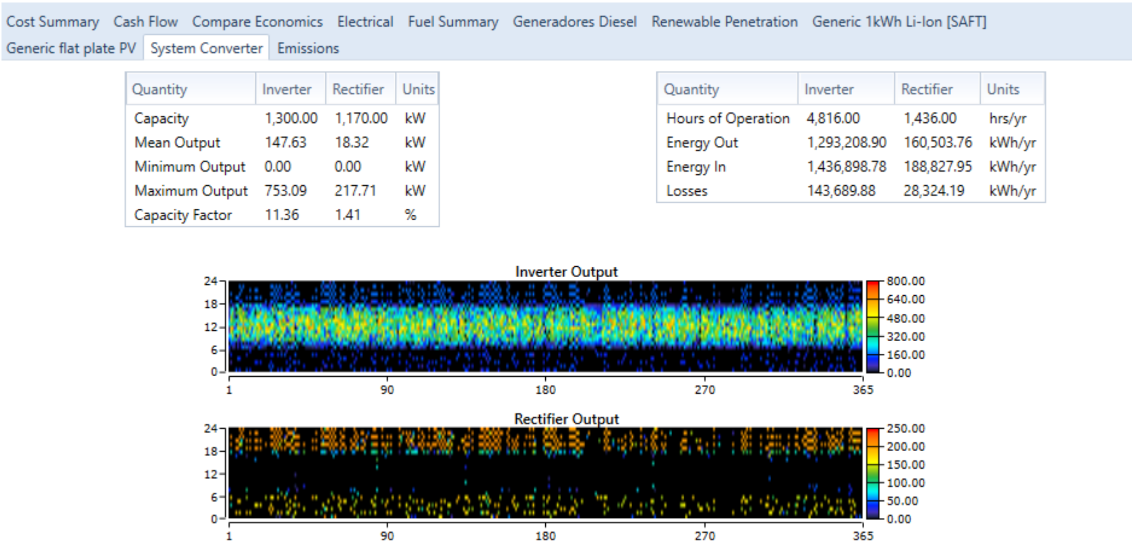


Figure 50: CC Battery Bank

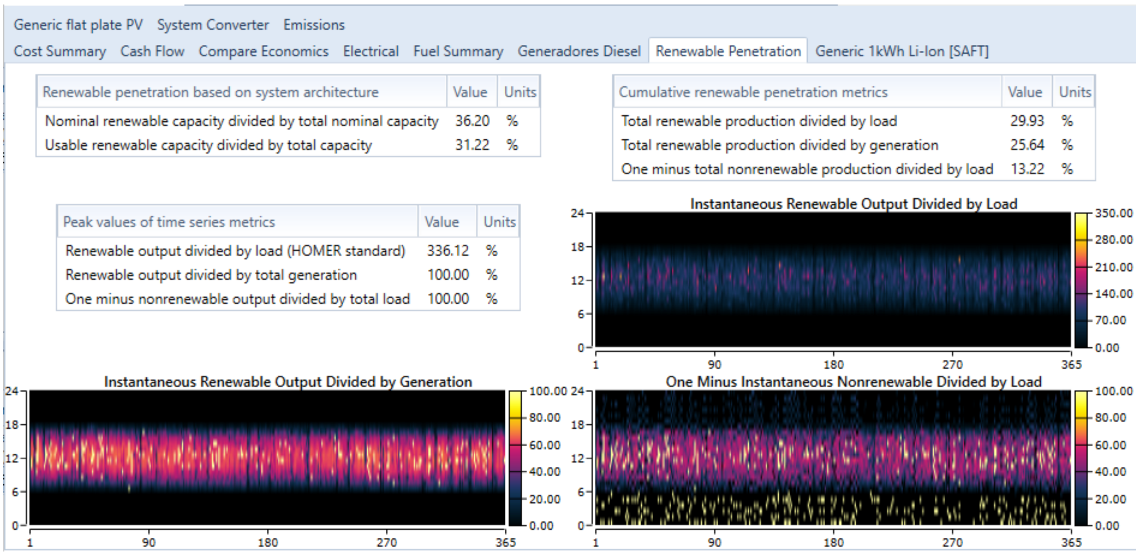
First, the schedule for the load and the generation from each component will be presented in Figure 54, Figure 55, Figure 56 and Figure 57, an then some other figures containing mixed data will be used to analyse the battery charging cycles, the renewable penetration and the way the load is met overall.
The load, represented in Figure 54, is the same as in the previous case.



Quantity	Inverter	Rectifier	Units
Capacity	1,300.00	1,170.00	kW
Mean Output	147.63	18.32	kW
Minimum Output	0.00	0.00	kW
Maximum Output	753.09	217.71	kW
Capacity Factor	11.36	1.41	%

Quantity	Inverter	Rectifier	Units
Hours of Operation	4,816.00	1,436.00	hrs/yr
Energy Out	1,293,208.90	160,503.76	kWh/yr
Energy In	1,436,898.78	188,827.95	kWh/yr
Losses	143,689.88	28,324.19	kWh/yr

Figure 51: CC Converter



Renewable penetration based on system architecture	Value	Units
Nominal renewable capacity divided by total nominal capacity	36.20	%
Usable renewable capacity divided by total capacity	31.22	%

Cumulative renewable penetration metrics	Value	Units
Total renewable production divided by load	29.93	%
Total renewable production divided by generation	25.64	%
One minus total nonrenewable production divided by load	13.22	%

Peak values of time series metrics	Value	Units
Renewable output divided by load (HOMER standard)	336.12	%
Renewable output divided by total generation	100.00	%
One minus nonrenewable output divided by total load	100.00	%

Figure 52: CC Renewable Energy Penetration

Quantity	Value	Units
Carbon Dioxide	3,771,604.77	kg/yr
Carbon Monoxide	9,309.67	kg/yr
Unburned Hydrocarbons	1,031.23	kg/yr
Particulate Matter	701.81	kg/yr
Sulfur Dioxide	7,574.04	kg/yr
Nitrogen Oxides	83,070.92	kg/yr

Figure 53: Emissions with CC Controller

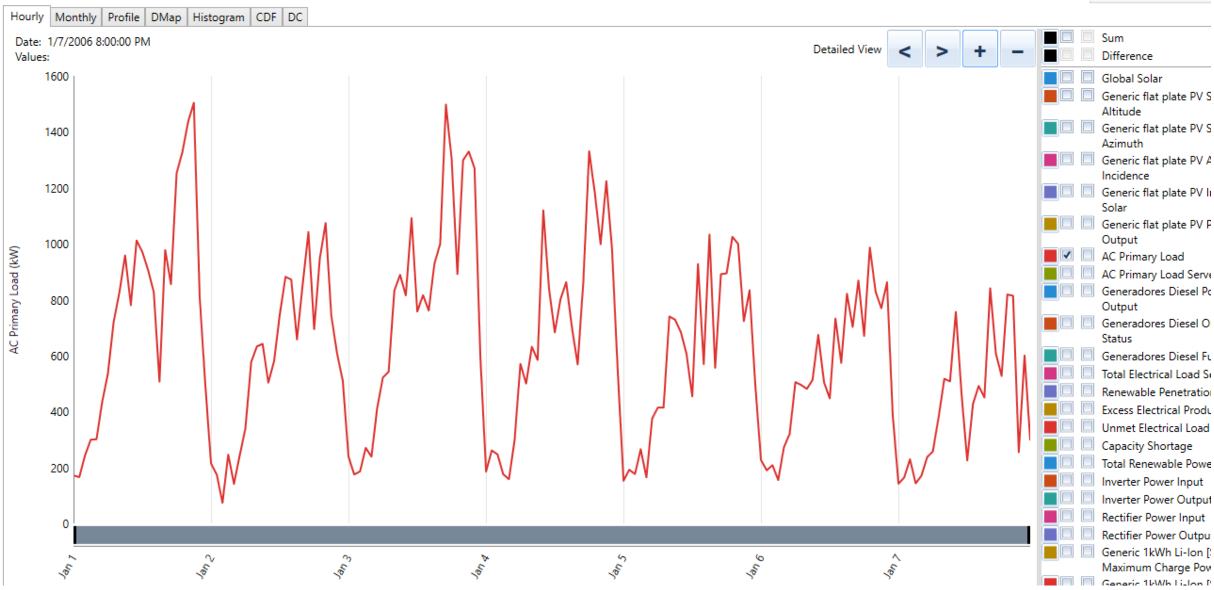


Figure 54: CC Primary Load on AC Bus

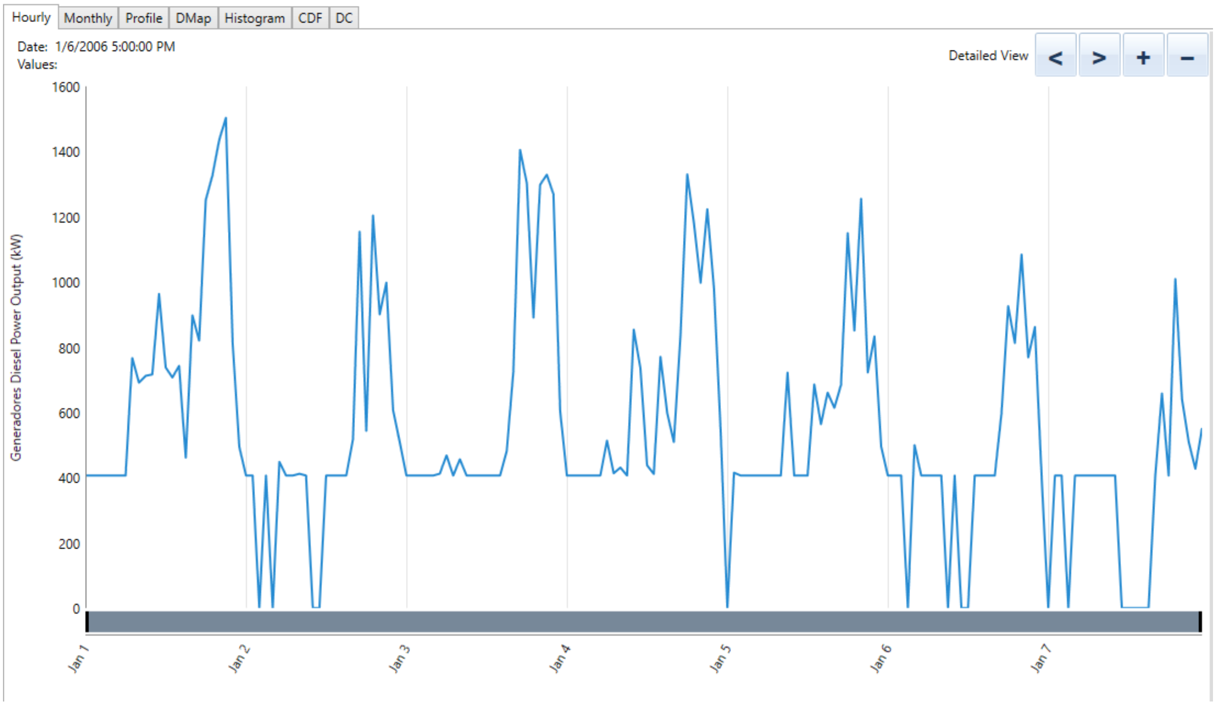


Figure 55: CC Generator Output (kW)

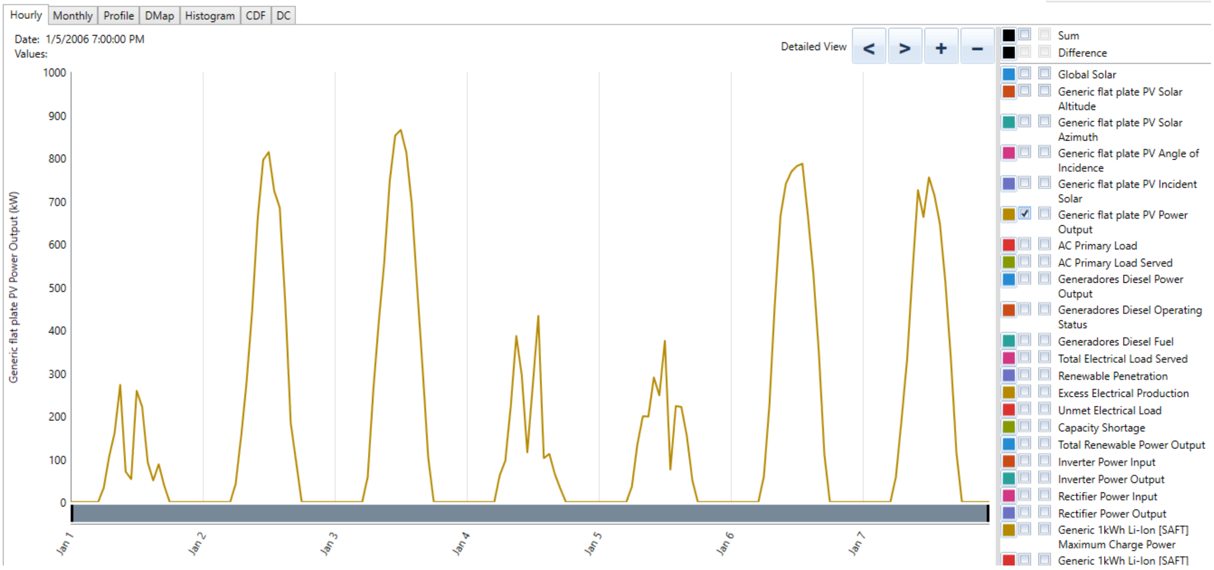


Figure 56: CC PV Output (kW)

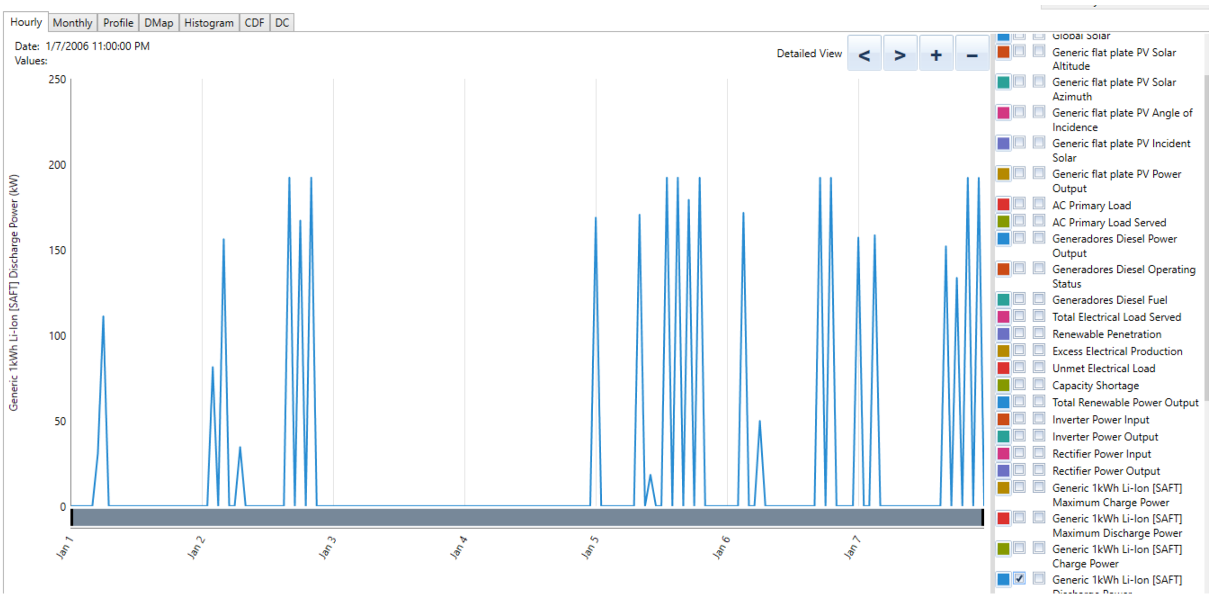


Figure 57: CC Battery Discharge (kW)

In Figure 58 the load has been plotted against all the previous generation curves from each component. As it can be appreciated most of the load is supplied by the diesel generator which is in operation most of the time. The solar production is the second biggest and the batteries only discharge when it is required to meet the load. For example, the 3^{rd} of January they did not discharge at all because the solar resource and the generator where enough to meet the demand.

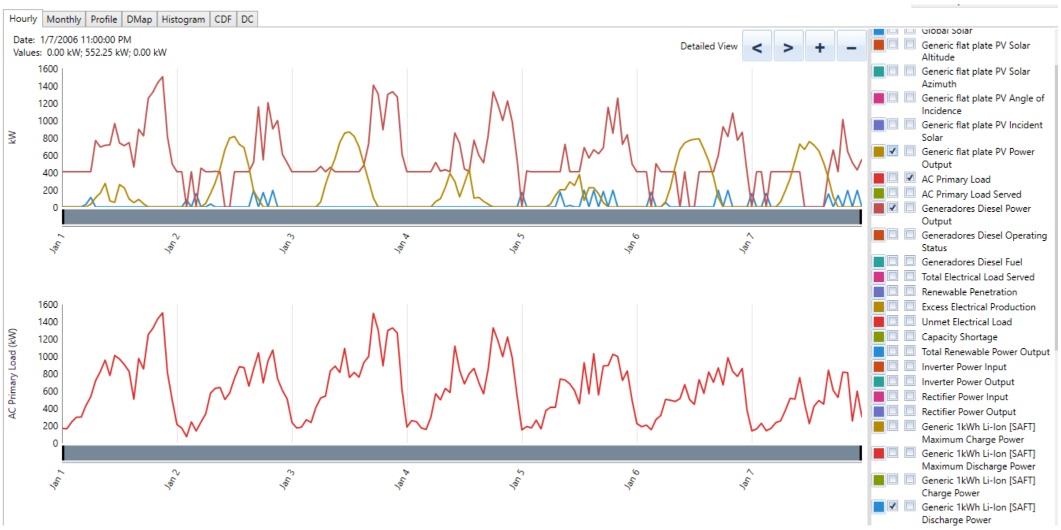


Figure 58: CC Load vs Generation (kW)

The following figures will be used to look into the use of the storage system.Figure 59 shows the state of charge of the batteries. It remains at 100% except during the periods in which discharge is required for generation.

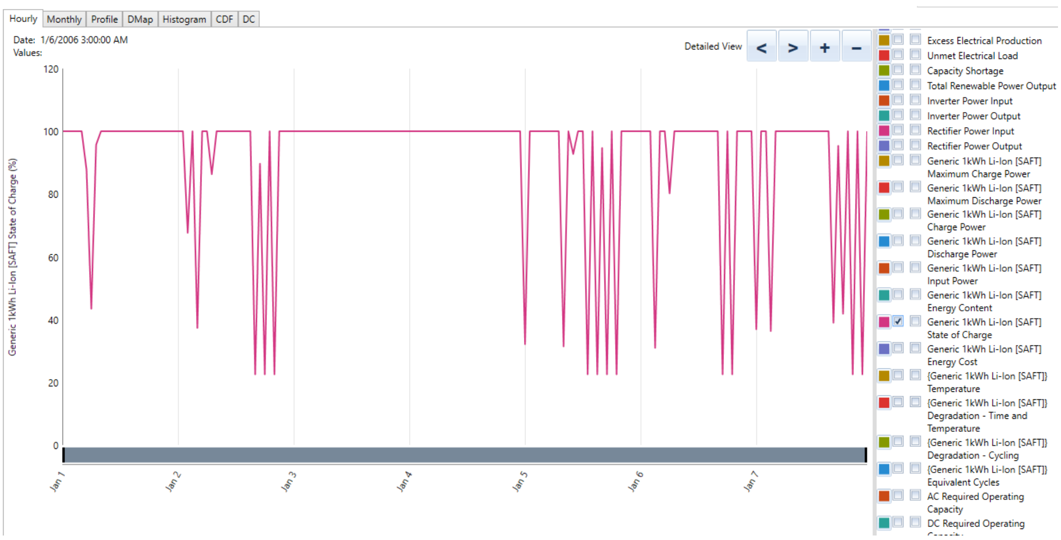


Figure 59: CC Batteries State of Charge (%)

Figure 60 shows the charge (in green) against the discharge (in blue) schedule. As it can be see, the charge occurs immediately after the discharge finished to return to the maximum state of charge.

Figure 61 combines the previous and plots them against all the generation curves, to present how they interrelate.

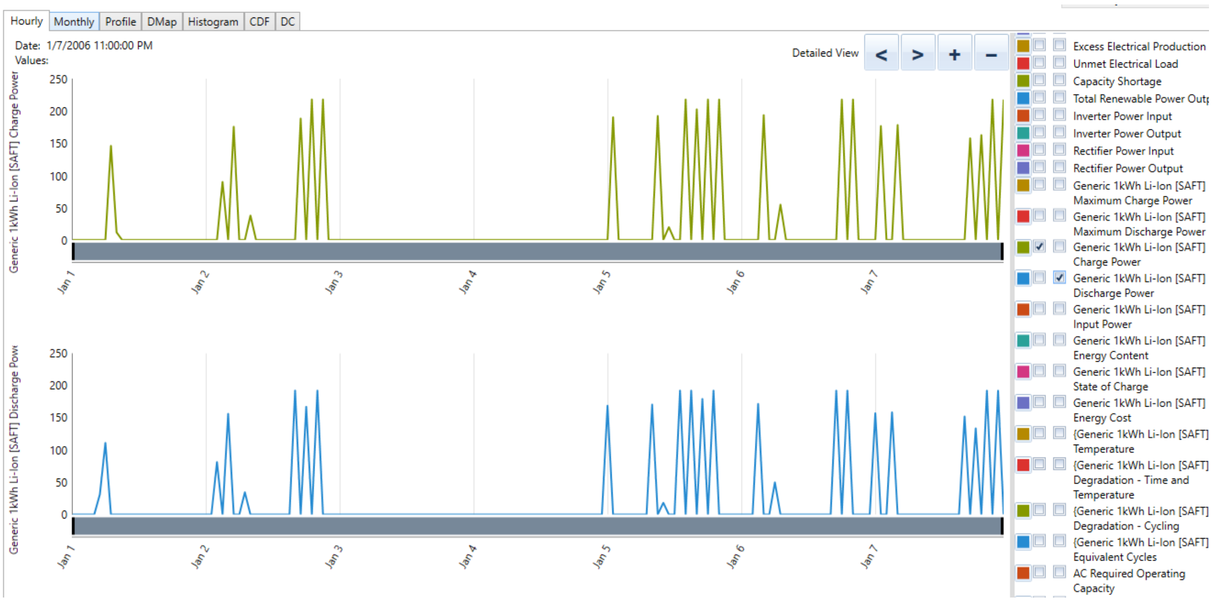


Figure 60: CC Batteries Charge vs Discharge (kW)

Figure 61: CC Batteries Charge/Discharge vs Generation (kW)

Last, Figure 62 shows the renewable generation against the total load supplied. It can be appreciated that although it is an important fraction of the total generation, it is not the largest one.

To conclude this section, Figure 63 presents a summary of the monthly electrical production that includes the production from each source, the renewable penetration and data about the continuity of the service.

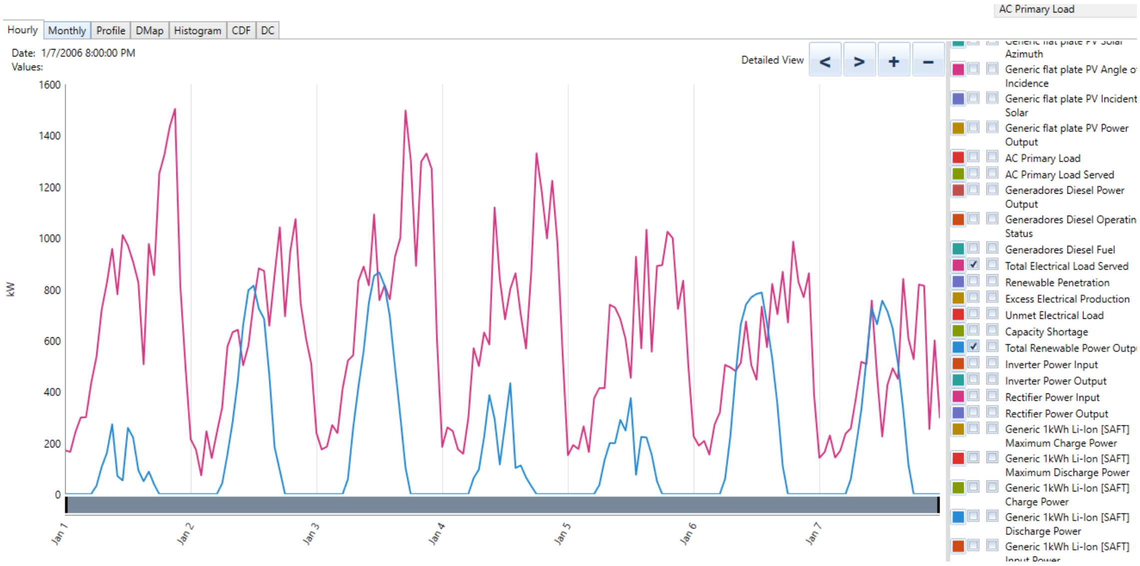
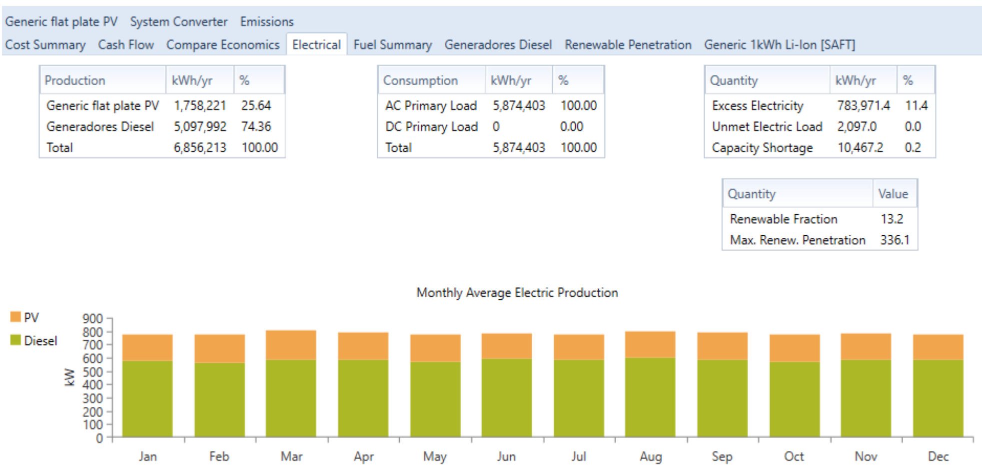


Figure 62: CC Renewable Generation against Load Served (kW)



Production	kWh/yr	%
Generic flat plate PV	1,758,221	25.64
Generadores Diesel	5,097,992	74.36
Total	6,856,213	100.00

Consumption	kWh/yr	%
AC Primary Load	5,874,403	100.00
DC Primary Load	0	0.00
Total	5,874,403	100.00

Quantity	kWh/yr	%
Excess Electricity	783,971.4	11.4
Unmet Electric Load	2,097.0	0.0
Capacity Shortage	10,467.2	0.2

Quantity	Value
Renewable Fraction	13.2
Max. Renew. Penetration	336.1

Figure 63: CC Summary of Monthly Production

4.4.3 MATLAB Link

MATLAB Link controller is a relatively new feature of HOMERPro. It was introduced in July 2016 along with the version 3.7, and it allows the users to define their one control strategy. To use this controller three functions are required: MatlabStartSimulation, MatlabEndSimulation, and MatlabDispatch. The first two have a predefined syntax, ad the third one is were they user actually writes the code that defines the dispatch schedule.
In this way, the users can define their own strategies to prioritize whatever they are most interested on: renewable generation,extending the batteries life, minimizing fuel consumption etc.
In this particular case, the implemented code aims to optimize the battery use, following a user defined cycle charging strategy. No charging set point has been considered, contrary to the previous section. The details on the strategy can be found in subsection 4.3.
In this case the controller definition is different from the previous cases. As shown in Figure 64, the user need to define:

- The path to the \bin\win32 folder in the MATLAB installation directory.
- The working directory where the three matlab functions are stored.
- The file names of the functions, which should just remain the same to avoid complications.

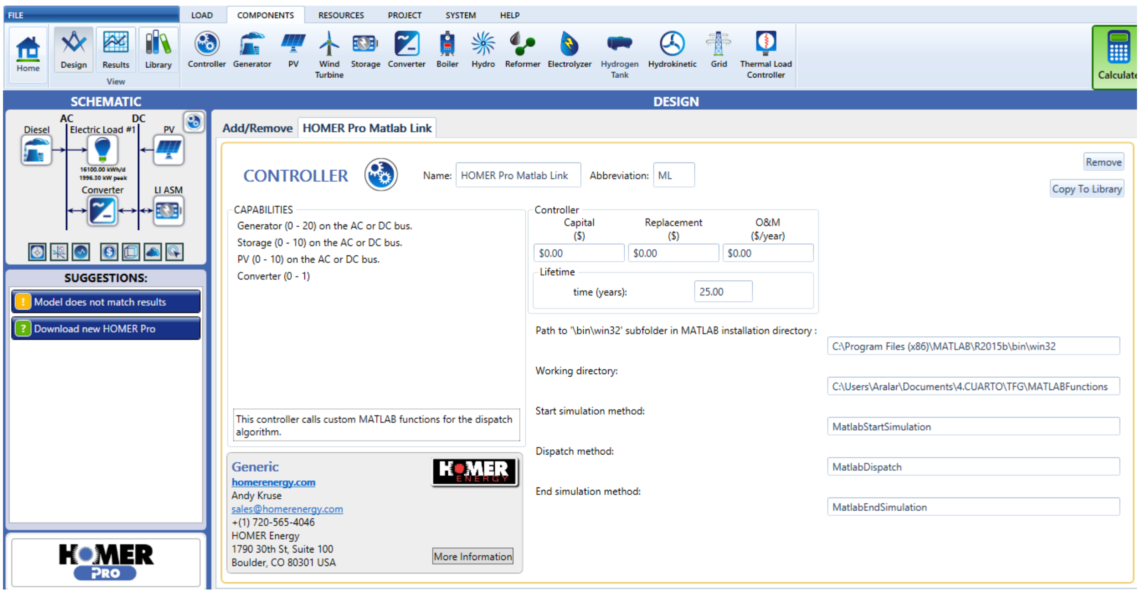


Figure 64: ML Controller

The settings regarding the cost of the controller and its lifetime have been left as default. In this case when we run the simulation it will take longer, but finally the results in Figure 65 come up.

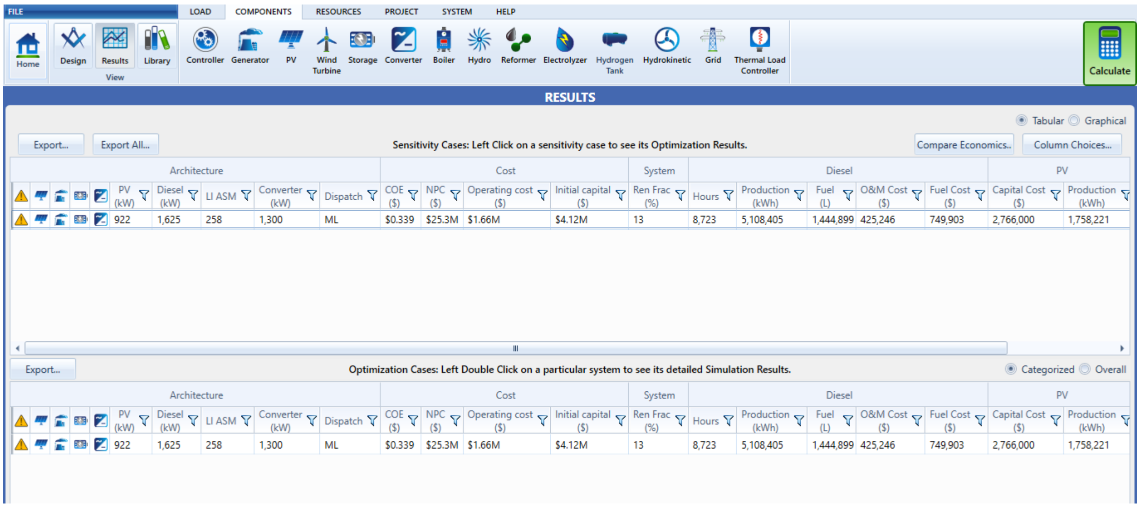
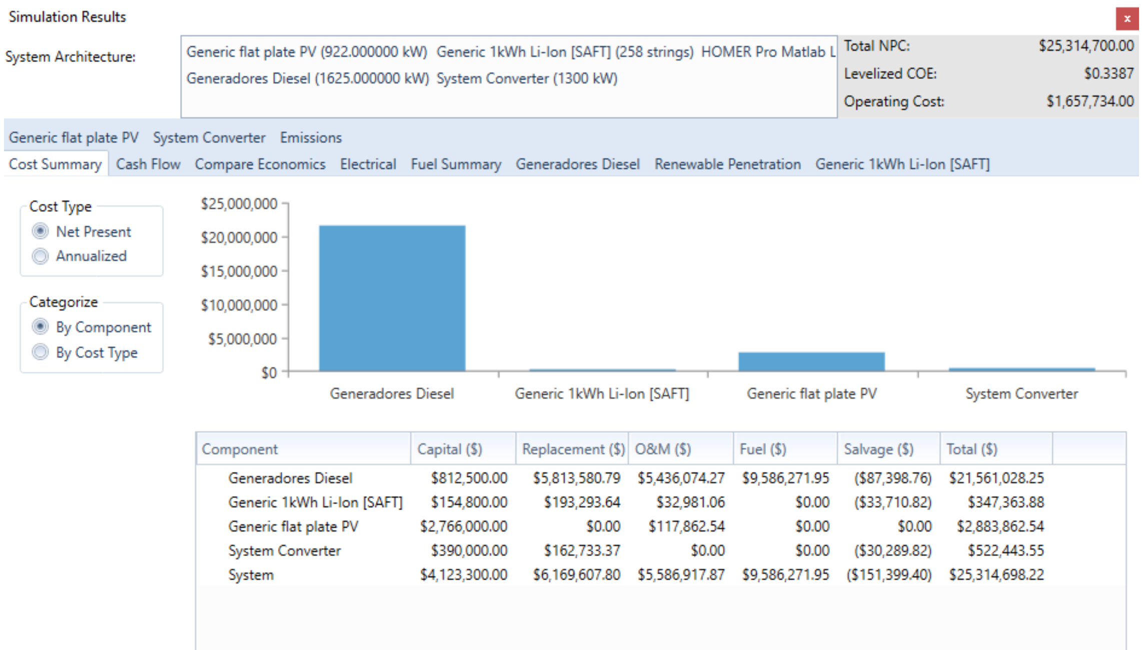


Figure 65: ML Simulation Results

As in the previous simulations, there is only one possible configuration.
Figure 66 shows a summary of the costs per component. As before, the main cost is associated to the generator due to the fuel consumption.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generadores Diesel	$812,500.00	$5,813,580.79	$5,436,074.27	$9,586,271.95	($87,398.76)	$21,561,028.25
Generic 1kWh Li-Ion [SAFT]	$154,800.00	$193,293.64	$32,981.06	$0.00	($33,710.82)	$347,363.88
Generic flat plate PV	$2,766,000.00	$0.00	$117,862.54	$0.00	$0.00	$2,883,862.54
System Converter	$390,000.00	$162,733.37	$0.00	$0.00	($30,289.82)	$522,443.55
System	$4,123,300.00	$6,169,607.80	$5,586,917.87	$9,586,271.95	($151,399.40)	$25,314,698.22

Figure 66: ML Costs Summary

Figure 67 shows the cash flow of this case. It is more similar to the cash flow with cycle charging than with load following, as there are less replacement flows, and the salvage income at the end of the 25 years is higher.

The main cost is therefore related to the fuel consumption. Figure 68 shows the

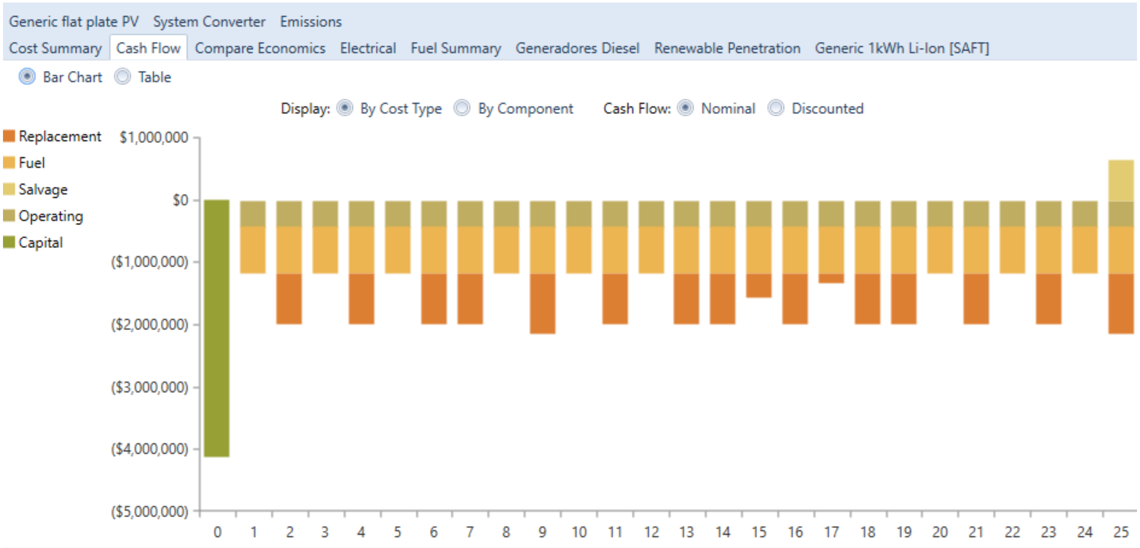


Figure 67: ML Cash Flow

detailed consumption of fuel during the year. July, August and November are the months with higher consumption. The average for all months is about 160 l/h.

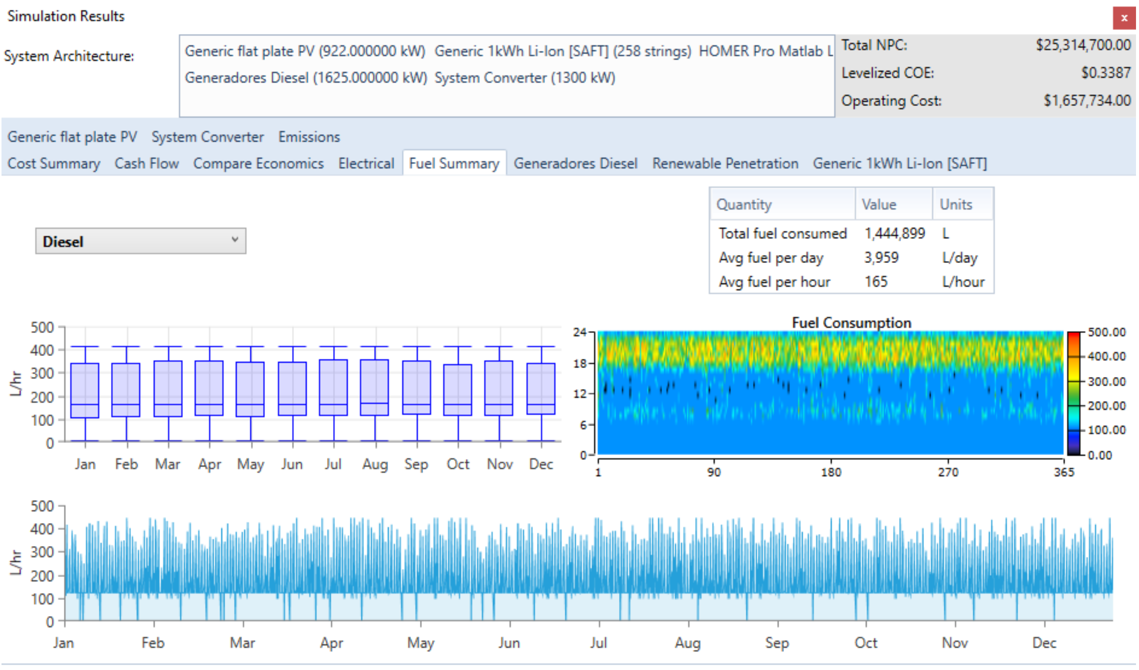


Figure 68: ML Fuel Usage

Figure 69 shows the generator. The production is similar to the one achieved with the cycle charging strategy, but the number of starts is a lot lower, only 35 against 433 with CC.

Figure 69: ML Diesel Generator Information

In Figure 70 the data about the PV collectors operation is displayed. Again the results are very similar to the previous cases, as the mean power output and the capacity factor remain at 200.7 kW and 21.77% respectively.

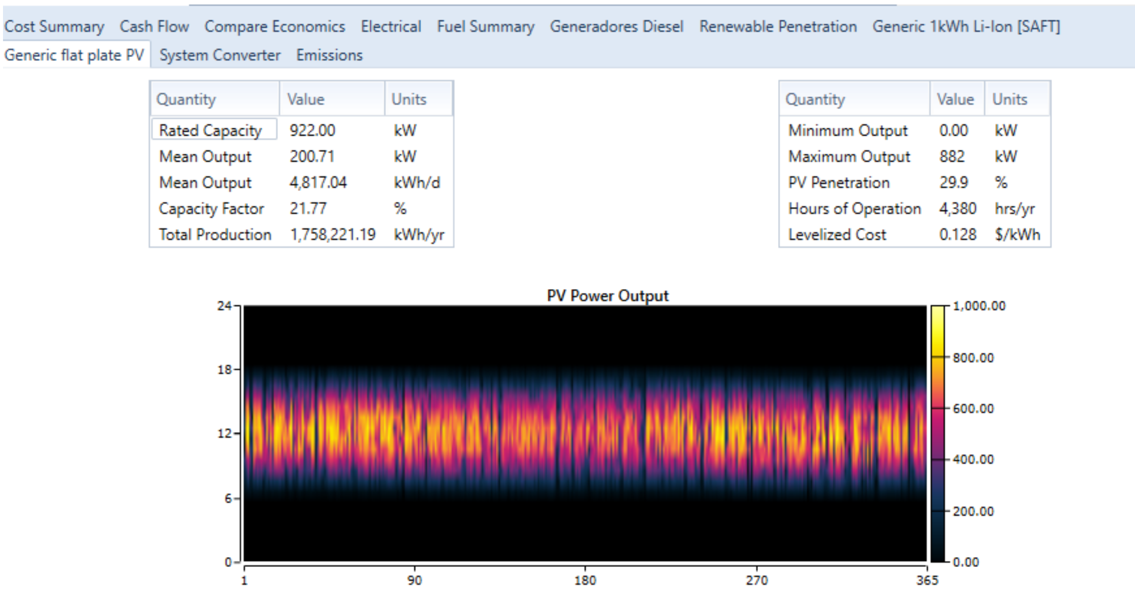


Figure 70: ML PV

In Figure 71 we can see that the battery use is somehow an intermediate point between the previous two cases. Although the state of charge remains higher than with the load following strategy, it is lower than with cycle charging. The batteries stay at a state of charge of 20% from 6 PM to roughly 00:00 AM. The rest of the time the charge is around 80%. According to the right lower graph, the state ov charge varies from 20 to 100%, with an average value of 70%. With this strategy their life is prolonged to 8.16 years.

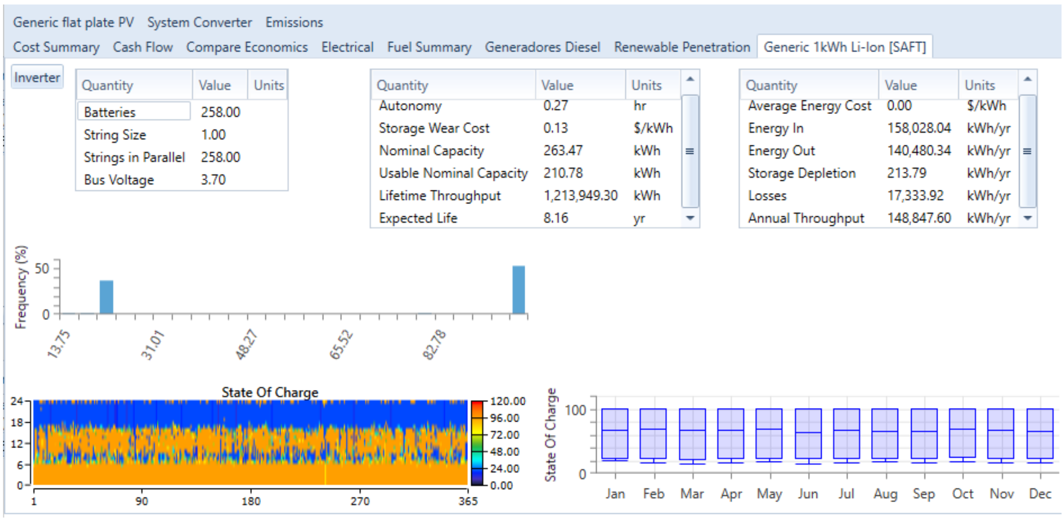


Figure 71: ML Battery Bank

The results from the converter are shown in Figure 72.

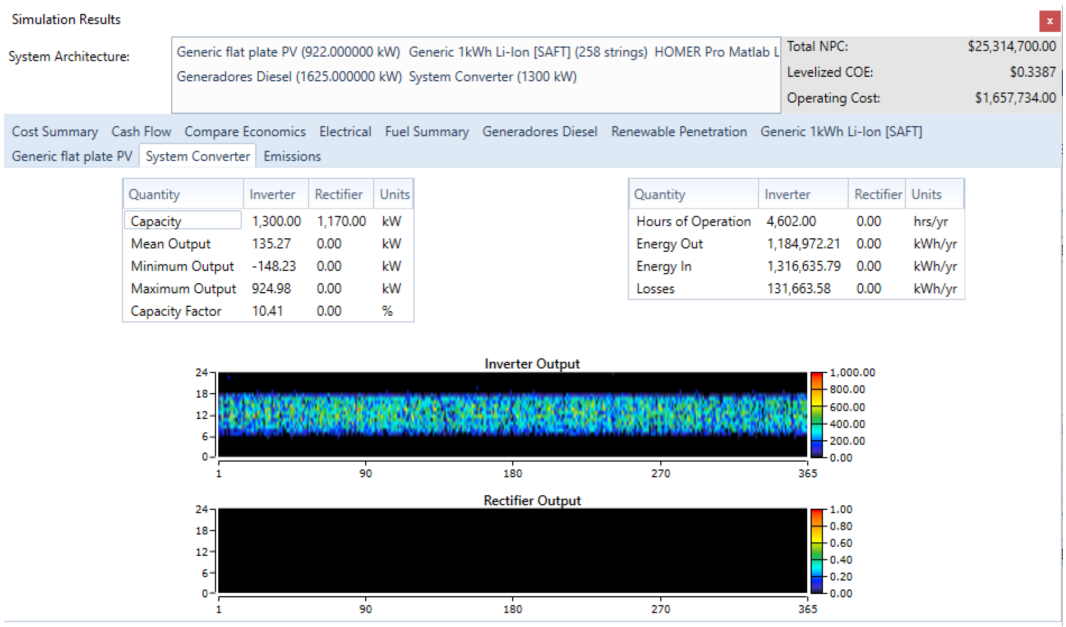


Figure 72: ML Converter

Figure 73 shows that the renewable penetration still remains at the same level with an average value of 36.2%. Let's recall that HOMERPro considers the power from the batteries discharge also renewable, so actually the net solar penetration would be lower.

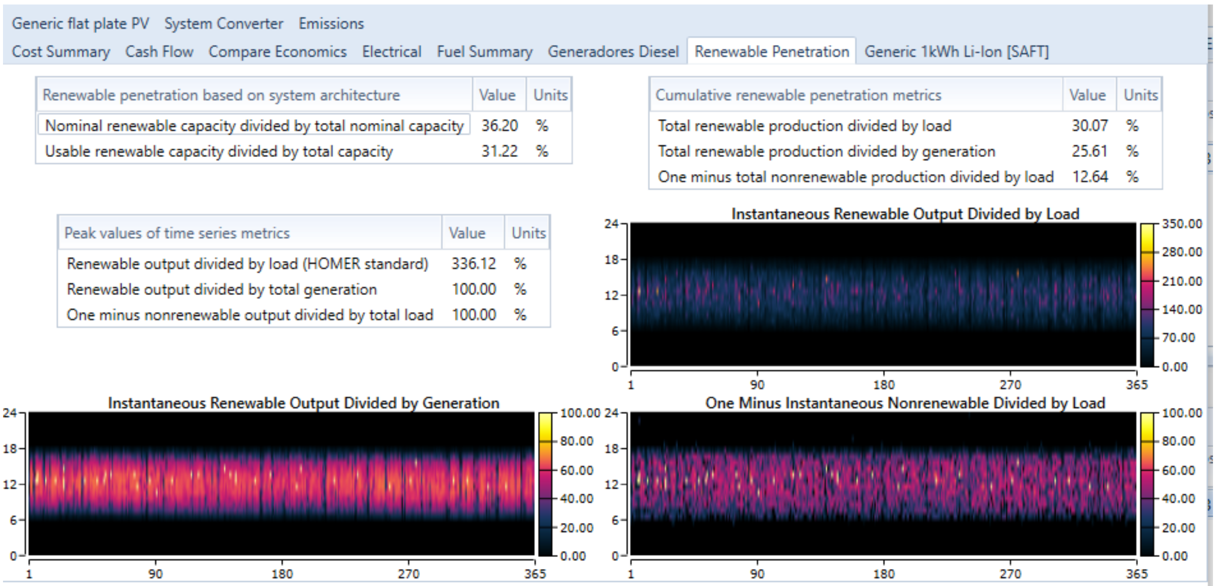


Figure 73: ML Renewable Energy Penetration

Before moving on onto the dispatch schedule results, Figure 74 shows the emissions resulting with the strategy implemented through MATLAB.

Quantity	Value	Units
Carbon Dioxide	3,804,894.78	kg/yr
Carbon Monoxide	9,391.84	kg/yr
Unburned Hydrocarbons	1,040.33	kg/yr
Particulate Matter	708.00	kg/yr
Sulfur Dioxide	7,640.89	kg/yr
Nitrogen Oxides	83,804.14	kg/yr

Figure 74: Emissions with ML Controller

As previously, the dispatch schedule resulting from the simulation will be presented through several graphs, taking as example the week from the 1^{st} to the 7^{the} of January.
To begin, the electrical load and the generation from each component will be presented. The electrical demand of the system can be found in Figure 75, and the generation from the generator, the PV modules and the storage system can be found in Figure 76, Figure 77 and Figure 78 respectively.

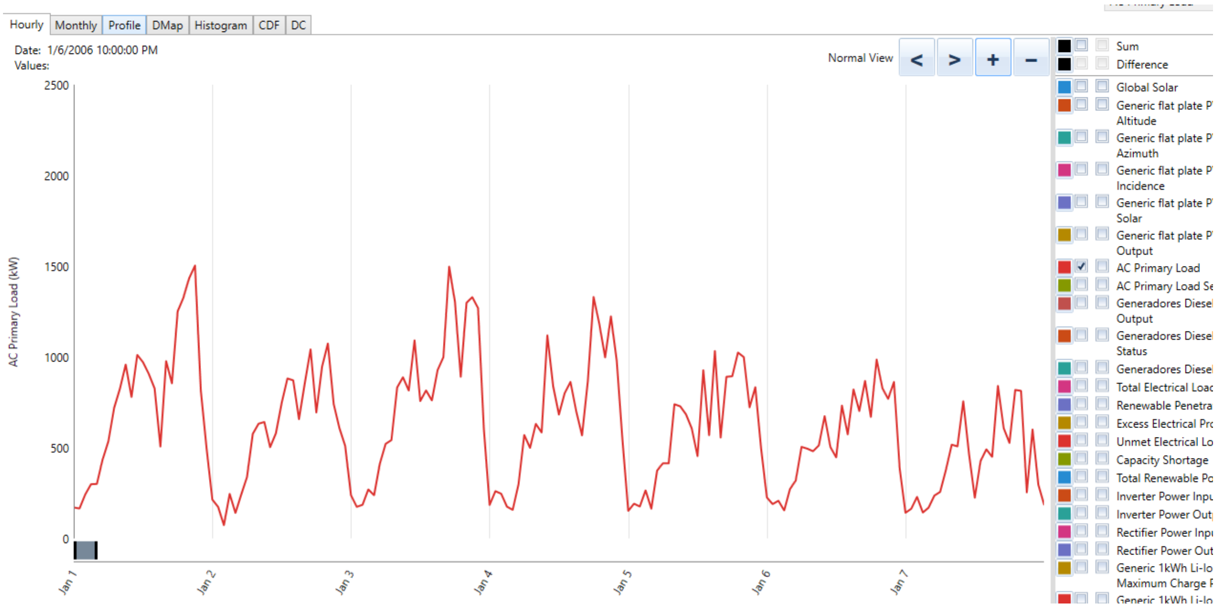


Figure 75: ML AC Primary Load (kW)

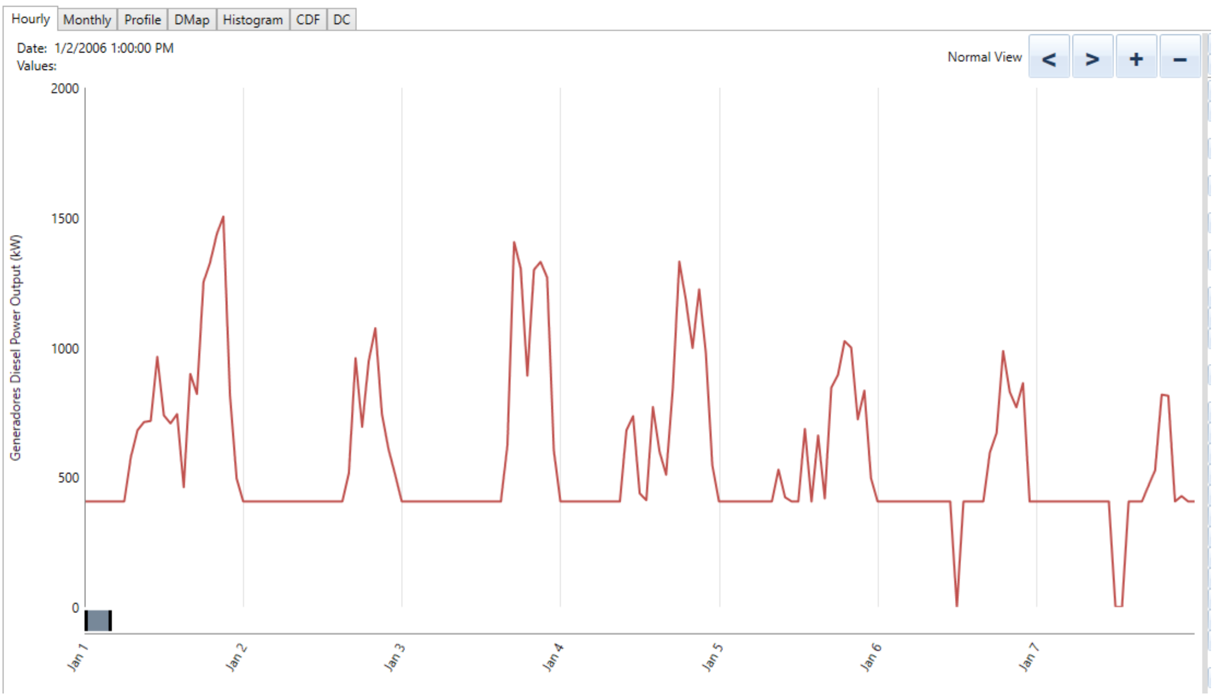


Figure 76: ML Generator Output (kW)

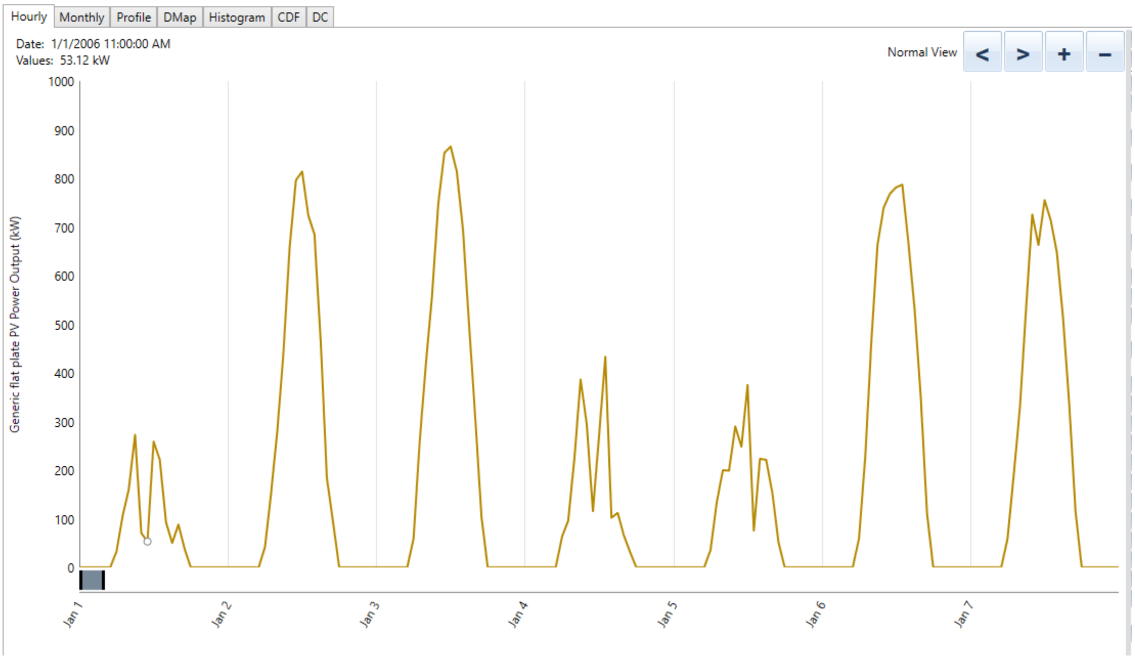


Figure 77: ML PV Output (kW)

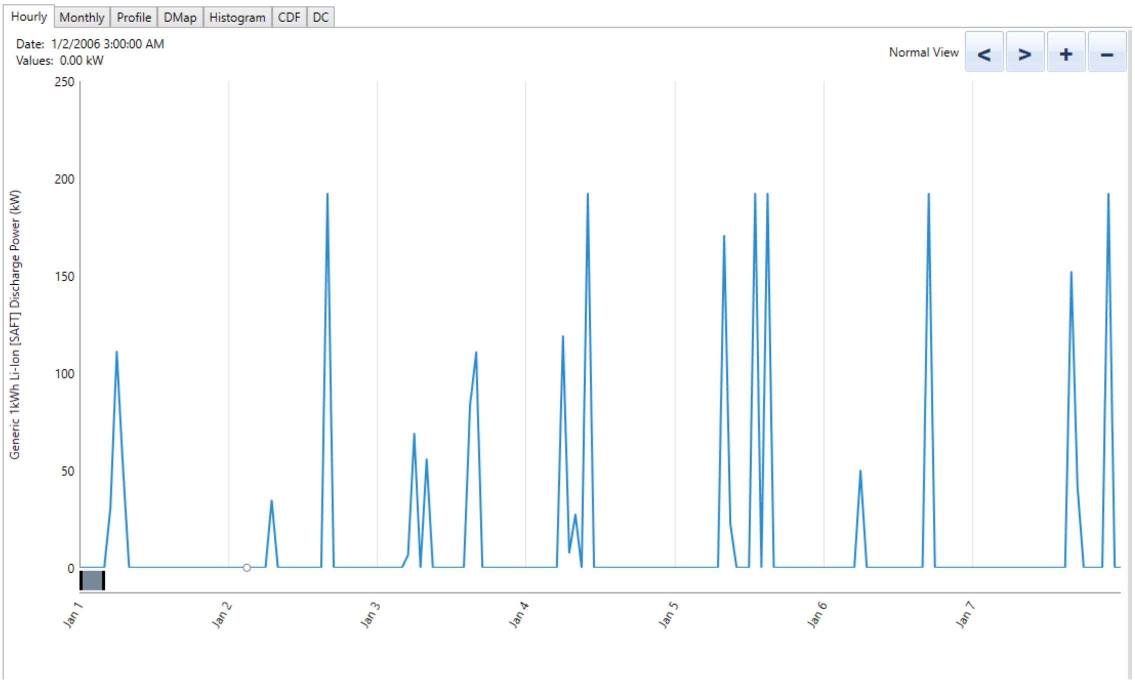


Figure 78: ML Battery Discharge (kW)

In Figure 79 the load has been plotted against all the previous generation curves from each component. As it can be appreciated most of the load is supplied by the diesel generator which is in operation most of the time. The solar production is the second biggest and the batteries only discharge when it is required to meet the load, which is usually twice or three times a day.

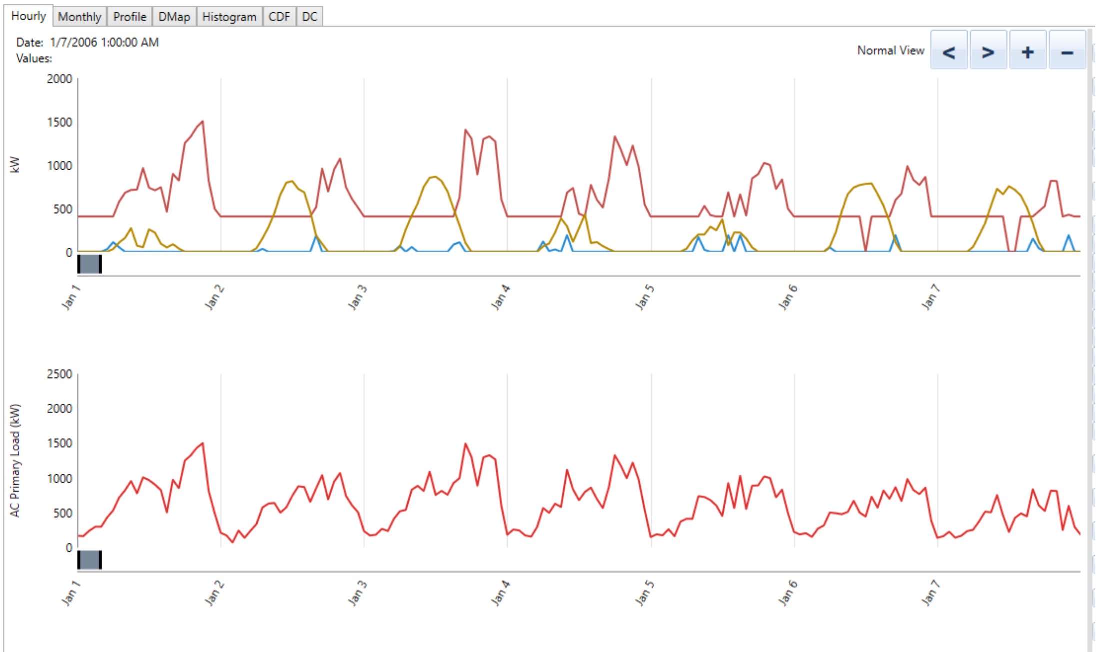


Figure 79: ML Load vs Generation (kW)

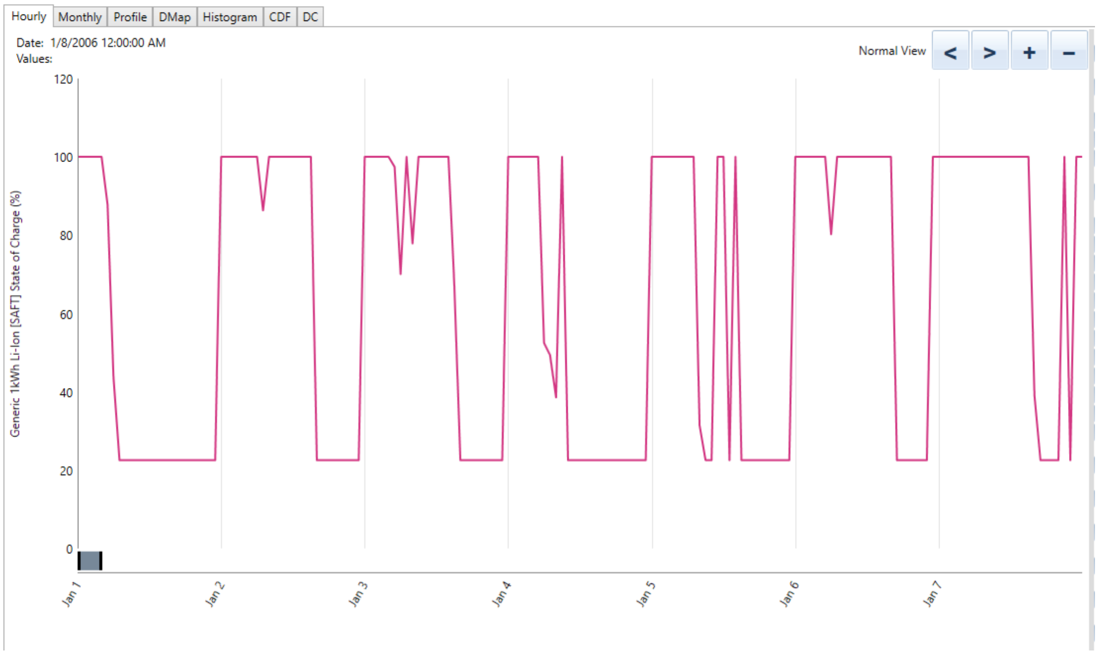


Figure 80: ML Batteries State of Charge (%)

Figure 80 hows the state of charge of the battery over the course of the week. Most of the time it stays at 100%, with periods of discharge down to 20%, which was the threshold value defined in the dispatch function.

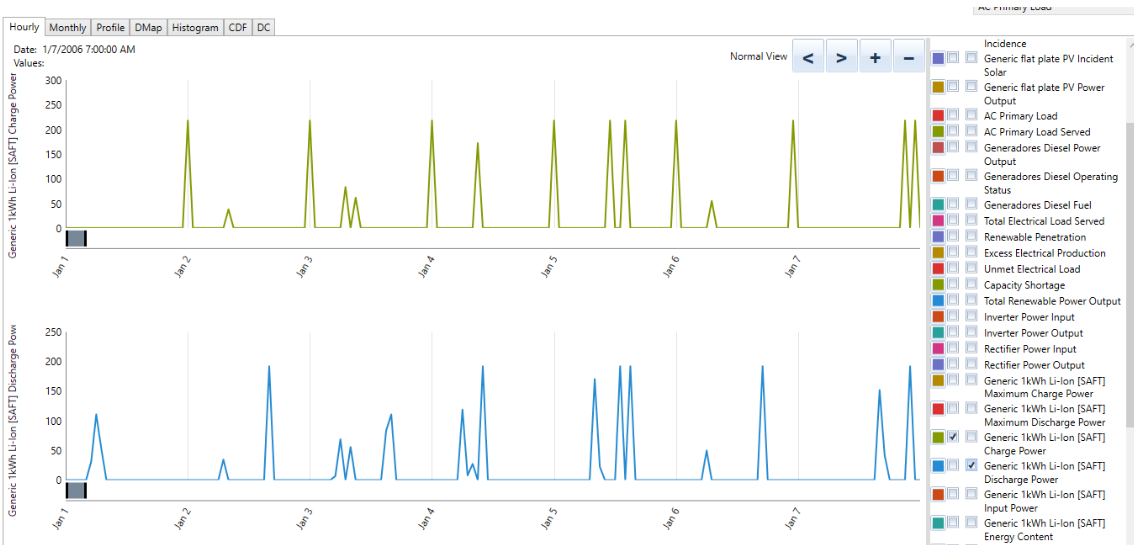


Figure 81: ML Charge vs Discharge (kW)

Above, Figure 81 shows the charging schedule (green) against the discharging schedule (blue).
Below, Figure 82 shows the previous graphs plotted together against all the generation. As we can see the charge usually takes place during peaks of the generator production.

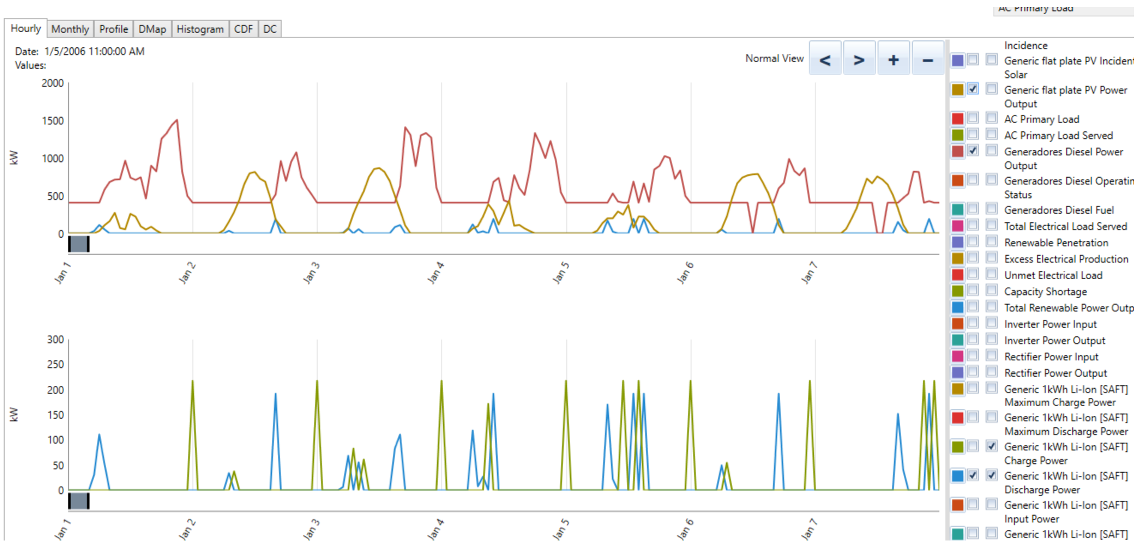


Figure 82: ML Charge/Discharge vs Generation(kW)

Overall the total renewable energy generation is plotted against the primary load served. Although for most of the time it remains well below the load, representing maybe around 30% of the total production there are momentary peaks of renewable generation that bring the renewable penetration to values above 100%.

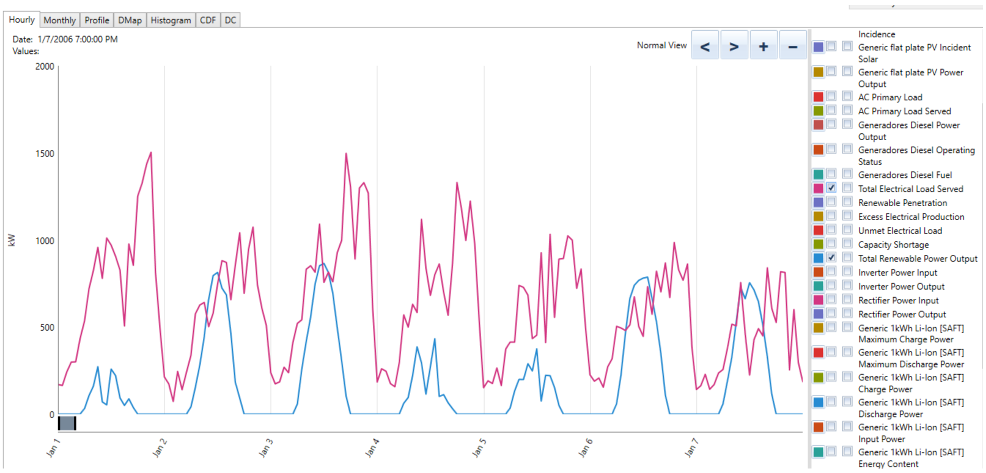


Figure 83: ML Renewable Generation against Load Served(kW)

To conclude, the monthly electrical production is presented in Figure 84.

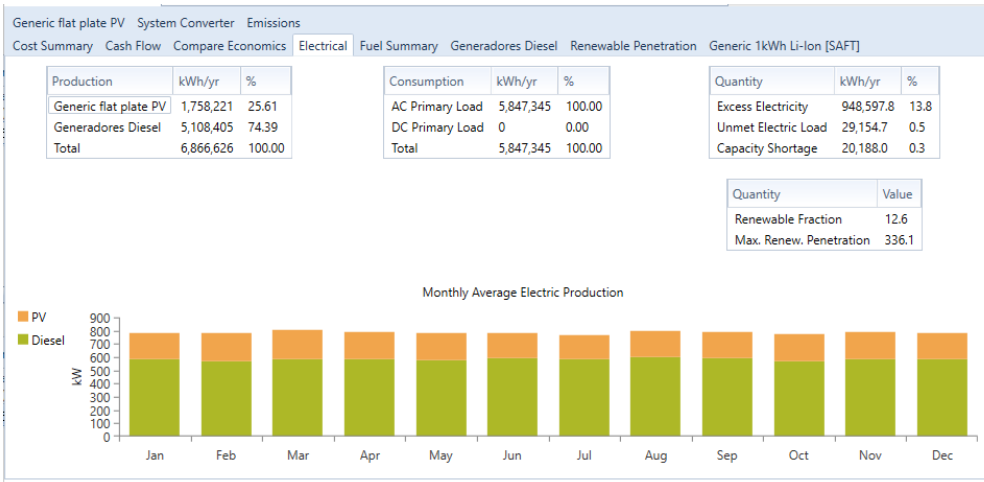


Figure 84: ML Summary of Monthly Production

4.4.4 Discussion

From the previous sections, we can extract that the major difference between the controllers is the level of use of the generator and the batteries charging strategy. In this section the results will be compared by means of the necessary tables and figures.
Table 5 shows the derived costs from each system and their performance

Table 5: System Costs and Renewable Fraction

	NPC	LCOE	Operational Cost	Generator Cost	Renewable Fraction
LF	\$24.6M	\$0.3273	\$1,599,188	\$20,790,000	15%
CC	\$24.74M	\$0.3295	\$1,612,939	\$20,833,000	13%
ML	\$25,31M	\$0.3387	\$1,657,734	\$21,561,028	13%

coefficients. This table has been created from Figure 23, Figure 44 and Figure 65. As it can be appreciated the load following strategy is the most efficient and it derives in the lowest net present cost. The reason four this is that the largest cost associated to the operation of the system, the fuel cost, is the lowest with this strategy as it is the one that runs the generator during less hours throughout the year. For the same reason the LF strategy incurs in a lower LCOE and generator cost, which also takes account the fuel consumption. Overall, this system achieves the highest renewable fraction, 15%, against only 13% of the other two. The renewable fraction is different form the renewable penetration, as it is related to the total renewable energy integrated into the grid instead of the instantaneous power generated. The renewable fraction is calculated according to Equation 6 and the renewable penetration according to Equation 7

$$f_{ren} = 1 - \frac{E_{nonren} + H_{nonren}}{E_{served} + H_{served}} \tag{6}$$

Where:E_{nonren} and H_{nonren} re the non renewable electrical and thermal production (kWh/year); and E_{served} and H_{served} are the electrical and thermal load served, respectively.

$$p_{ren} = \frac{P_{ren}}{L_{served}} \tag{7}$$

Where: P_{ren} is total renewable electrical power output in each time step(kW) and L_{served} is the total electrical load served in each time step (kW).
From Figure 27, Figure 48 ad Figure 69 Table 7 has been created, and from the data in Figure 26, Figure 47 and Figure 68 Table 9 has been built. From these tables we can see that with the MATLAB controller the generator is in operation 366 hours more than with the LF and 444 hours more than with the CC controller. This is also reflected in the number of starts, only 35 for the MATLAB controller but 356 and 433 for the LF and CC controllers respectively. They all present similar capacity, which means that they operate at similar levels as is confirmed

Table 7: Generator Operational Results

	Hours of operation	No. Of Starts	Operational Life	Capacity Factor	Production (kWh/year)	Mean Output (kW)
LF	8357h	356	1.79 years	35.90%	4,969,861.12	594.69
CC	8279h	433	1.81 years	35.80%	5,097,991.74	615.77
ML	8723h	35	1.72 years	35.90%	5,108,404.84	585.65

Table 9: Fuel Consumption

	Fuel Consumption	Fuel Cost
LF	1402768 L/year	\$728,036
CC	1432257 L/year	\$743,342
ML	1444898 L/year	\$749,903

by the mean power output. However the difference it time of operation causes the system with the ML controller to produce a higher net energy throughout the year. This higher production drives uo the fuel consumption as can be seen in Table 9, and the associated cost. This cost represents the largest fraction of the operational cost and therefore also drives up the LCOE.
The LCOE is affected by several costs, among them we should highlight the operational cost and the replacement cost, as the LCOE i calculated for the whole life of the installation, in this case 25 years. The replacement cost will be affected by the life of the batteries. To analyse the operation of the batteries Table 10 is presented:

Table 10: Storage System Operation Results

	LF	CC	ML
Expected Life(years)	7.53	5.73	8.16
Energy input (kWh/year)	174,238	228,675	158,028
Energy output (kWh/year)	155,734	202,850	140,480
Losses (kWh/year)	18,297	25,811	17,334
Annual Throughput (kWh)	164,906	215,407	148,847
Life Throughput (kWh)	1,241,569	1,235,268	1,213,949

The parameter that presents more changes is the batteries expected life. HOMERPro calculates the expected life according to Equation 8.

$$R_{batt} = Min(\frac{N_{batt}Q_{lifetime}}{Q_{thrpt}}, R_{batt,f}) \tag{8}$$

Where: N_{batt} is the number of batteries, $Q_{lifetime}$ is the life throughput, Q_{thrpt} is the annual throughput, and $R_{batt,f}$ is the float lifetime of the battery. The last

variable is for those storage systems limited by time. In this case, the batteries are limited by throughput.
As the battery activity is more intense under the cycle charging strategy, this is also the strategy that shortens more the expected life of the storage system. The reason for this is that under this strategy whenever the state of charge is below 80% and there is leftover power from the generators they batteries will be charged, whereas the other two systems have lower annual throughputs. The ML dispatch strategy on the other hand is the one that maximizes the expected life of the batteries due to the conditions imposed. Also, the discharges are less frequent with the ML strategy, and have the highest frequency under the CC strategy, as can be seen in Figure 85,Figure 86 and Figure 87.

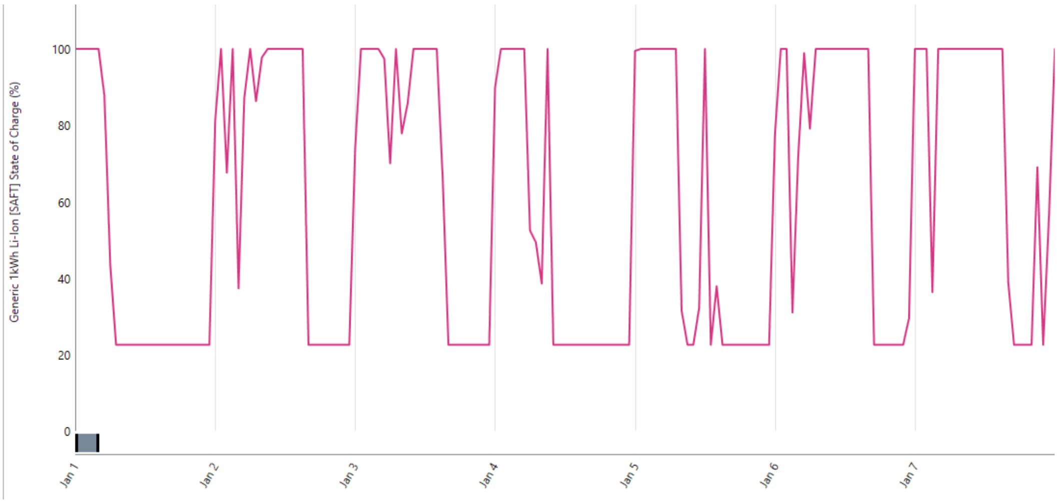


Figure 85: State of Charge under LF Strategy(%)

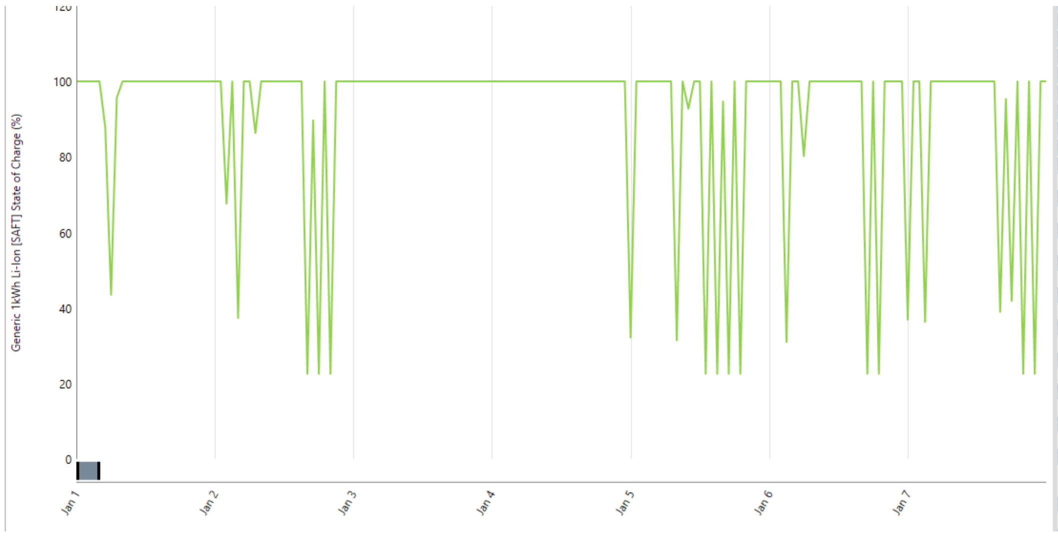


Figure 86: State of Charge under CC Strategy(%)

Last of all Table 11 shows the emissions caused by each controller. As it could be

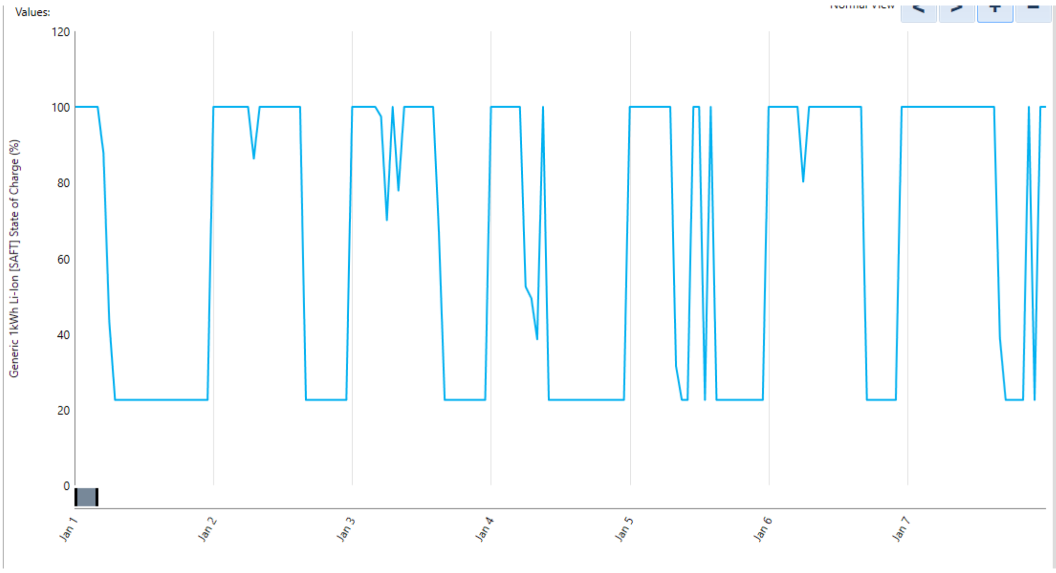


Figure 87: State of Charge under ML Strategy(%)

expected, the Load Following strategy is the most environmentally friendly option regarding emissions, as the solar penetration is higher.
Regarding the emissions, CO_2, SO_2 and some NO_x are the gases that can produce

Table 11: Emissions from each System

	LF	**CC**	**ML**
CO_2**(tons/year)**	3693.95	3771.60	3804.90
CO (tons/year)	9.12	9.31	9.39
C_xH_y **(tons/year)**	1.01	1.03	1.04
Particulate Matter (tons/year)	0.69	0.70	71.00
SO_2 **(tons/year)**	7.42	7.57	7.64
NO_x **(tons/year)**	81.36	83.07	83.80

more harm. NO_x and SO_2 in particular have adverse health effect and can cause acid rain. Moreover, Particulate matter can also damage the health of both humans and the species of the islands. This is another reason to try to reduce the emissions eve further by decreasing the fuel consumption in the islands, because even if spilling disasters are avoided the use of this fuels still damages the ecosystem.[48]

5 Socio-Economic Environment

5.1 Project costs

The cost of the projects are given by the software HOMERPro. The annual cash flows can be found in Figure 25, Figure 46 and Figure 67 for the load following, cycle charging and MATLAB ems options.
The three of them have a initial investment associated of $4.12 million, but due to the different energy management strategies they incur in different net present costs, as was shown in Table 5, in particular they are $24.6M with the LF controller, $24.74M wtuh CC and $25.31M with ML. Overall the levelized cost of energy turns out to be $ 0.3273, $0.3295 and $0.3387. The NPC and the LCOE are the two main indicators of the economical efficiency of each option and the aim is to minimize both of them, therefore it can be stated that the LF controller is the best option economically wise.

5.2 Social Impact

This project will impact the society in Isabela in diverse ways.
First, jobs related to the operation of the system will be created, requiring different levels of training and educational backgrounds. Considering the role of tourism in the islands economy, this hobs will be more regular as they will not depend in seasonal trends.
Secondly, the first aim of the project is to make electricity generation more environmentally friendly. This will benefit the island from a health perspective by reducing the CO_2 and other harmful emissions. It will also benefit the surrounding ecosystem, which will benefit not only from reduced emissions but also from a reduced risk in fuel spilling when it is transport by ship into the archipelago. Last of all, the improvement in the natural preservation of the island also has an effect on its economy, because as it has already been mentioned several times, it has evolved around tourism. Is it precisely the nature and endemic species that attract millions of tourists to this secluded enclave every year, and to keep the flow of visitors the ecosystem has to be preserved. Otherwise it will suffer environmental impacts as has already happened in other parts of the world such as the Australian Great Barrier Reef.

6 Conclusions

In order to reduce the fossil fuel dependency of the archipelago a good design of the energy management system is essential, not only to ensure the continuity of the supply despite the integration of electricity from non-dispatchable sources, but also to guarantee that each technology is operated appropriately according to its needs.

Taking into account the growing population and growing demand of the archipelago, additional power installation will be required in the upcoming years, therefore an energy management system that allows the maximum renewable penetration will be needed to obtain the maximum benefit out of these technologies not only economically but also from an environmental point of view.

Out of the three models proposed the one that reduces more the fuel dependency is the load following strategy. It reduces the costs and provides the highest solar penetration. The cycle charging strategy maximizes the use ob the storage system, which is the opposite of the desired result due to the nature of the materials of which batteries are made and their current market price. The EMS implemented through MATLAB on the other hand provides the best management of the storage system but it also drives the fuel consumption and consequently the operational costs up.

However it must be highlighted that the MATLAB link function of HOMER Pro is still under development. During the simulation of the last case the software presented many limitations as the fact that some technologies cannot be yet included in the user EMS, forecast of the demand or the solar resource cannot be introduced either. Nevertheless this software has a great potential for the design of energy management, and once this feature reached a higher degree of maturity, it can be a very powerful tool to design and test different energy management systems according to the needs of the project.

As it was related in section 2.3, the forecast of the solar resource is essential to provide a flexible and reliable supply which counteracts for the variable nature of the resource. Therefore, future improvements to take into account include the addition of forecast of the solar resource by means of ANNs. The solar forecast would allow a better management of all the technologies but should be specially be taken into account in the schedule of charge and discharge of the storage system. Including a prediction of the demand can also enable to manage better the system in a similar way than solar forecast does. However, as it was mentioned before this is for now beyond the competences of HOMER Pro.

A MatlabStartSimulation Function

```
function [myErr, matlab_simulation_variables] = MatlabStartSimulation(simulation_parameters)
myErr.error_description = '';
myErr.severity_code = '';
matlab_simulation_variables.total_energy_test = 0;
matlab_simulation_variables.gen1_CO = 0;
end
```

B MatlabEndSimulation Function

```
function myErrs = MatlabEndSimulation(simulation_parameters, matlab_simulation_variables)
myErrs.simulation_errors = {};
myErrs.simulation_warnings = {};
end
```

C Matlab Dispatch Function

```
function [simulation_state, matlab_simulation_variables] = MatlabDispatch(simulation_parameters, simulation_state, matlab_simulation_variables)

% Checking that there are PV collectors and assigning them their output


    if simulation_parameters.has_pv==true
        simulation_state.pv(1).power_setpoint = simulation_state.pv(1).power_available;
    end
%First IF condition: cheking if the stateof charge of the ESS is above or
%below 20%
if simulation_parameters.has_battery==true && simulation_state.battery(1).state_of_charge_percent > 20
    %The battery is initialized to be neither charging nor discharging. If
    %the setpoint is negative it will indicate the discharge rate and if it
    %is negative the charge rate.
    simulation_state.battery(1).power_setpoint = 0;
```

```
    actually_inverted_power = min(simulation_parameters.
        converter(1).inverter_capacity,(simulation_state.
        pv(1).power_setpoint-simulation_state.battery(1).
        power_setpoint).*simulation_parameters.converter
        (1).inverter_efficiency/100);
% 2nd IF condition: the generator will go into operation
    when the PV alone
% meet the load or when the converter use is minimized.
    if simulation_parameters.has_generator==true && (
        simulation_state.ac_bus.load_requested-
        actually_inverted_power)>0
        gen_power_available = simulation_state.generator
            (1).power_available;
        gen_min_load = simulation_parameters.
            generator_list(1).minimum_load;
        electrical_load = simulation_state.ac_bus.
            load_requested;
        % 3rd IF condition: checks the required generator
            output
        if gen_power_available > electrical_load &&
            gen_min_load < electrical_load
            %The load can be met at minimum load.
            simulation_state.generator(1).power_setpoint
                = gen_min_load; %()()()
            %4th IF condition: The batteries setpoint id
                defined to satisfy
            %the system requirements. need_from_batt is
                the power batteries
            %need to provide (discharge) to meet the
                demand
            required_from_batteries= simulation_state.
                ac_bus.load_requested-simulation_state.
                generator(1).power_setpoint-(
                simulation_state.pv(1).power_setpoint*
                simulation_parameters.converter(1).
                inverter_efficiency/100);
            if required_from_batteries < 0 %If the
                discahrge is not required, and in fact
                there is excess energy the batteries will
                 charge
                if simulation_state.battery(1).
                    state_of_charge_percent < 40 && -
                    required_from_batteries <
                    simulation_state.battery(1).
                    max_charge_power
                    simulation_state.battery(1).
                        power_setpoint = -
```

```
                        required_from_batteries; %(-)*(-)=(+)--> charge
                    actually_inverted_power = min(simulation_parameters.converter(1).inverter_capacity,(simulation_state.pv(1).power_setpoint-simulation_state.battery(1).power_setpoint).*simulation_parameters.converter(1).inverter_efficiency/100);
                else
                    simulation_state.battery(1).power_setpoint = simulation_state.battery(1).max_charge_power;
                    actually_inverted_power = min(simulation_parameters.converter(1).inverter_capacity,(simulation_state.pv(1).power_setpoint-simulation_state.battery(1).power_setpoint).*simulation_parameters.converter(1).inverter_efficiency/100);
                    %The batteries are charged with power from the PV
                    %collectors, therefore the inverted power is reduced.
                end
            else %The batteries are required to provide power: required_from_batteries>0
                if required_from_batteries < simulation_state.battery(1).max_discharge_power
                    simulation_state.battery(1).power_setpoint = -required_from_batteries./(simulation_parameters.converter(1).inverter_efficiency/100);
                    actually_inverted_power = min(simulation_parameters.converter(1).inverter_capacity,(simulation_state.pv(1).power_setpoint-simulation_state.battery(1).power_setpoint).*simulation_parameters.converter(1).inverter_efficiency/100);
                else
```

```
                simulation_state.battery(1).power_setpoint = - simulation_state.battery(1).max_discharge_power; % (-) --> discharge
                actually_inverted_power = min(simulation_parameters.converter(1).inverter_capacity,(simulation_state.pv(1).power_setpoint-simulation_state.battery(1).power_setpoint).*simulation_parameters.converter(1).inverter_efficiency/100);
                %After providing the maximum power from the batteries the
                %generator setpoin is updated to provide the neccessary
                %power to meet the load, as with the batteries it is not
                %yet enough
                ac_power_needed = simulation_state.ac_bus.load_requested-actually_inverted_power;
                simulation_state.generator(1).power_setpoint = ac_power_needed;
            end
        end
        %Here ends the definition of the batteries setpoint.

        % The input and output of the inverter and defined.
        converted_power_required = min(simulation_state.ac_bus.load_requested-simulation_state.generator(1).power_setpoint,actually_inverted_power);
        simulation_state.converter(1).inverter_power_output = converted_power_required;
        simulation_state.converter(1).inverter_power_input =  simulation_state.converter(1).inverter_power_output/(simulation_parameters.converter(1).inverter_efficiency/100);

    elseif gen_power_available > electrical_load %()()()
```

```
            %With the generator operating at minimum load is enough to meet
            %the demand. If there is excess electricity it will be used to
            %charge the batteries in case their state of load is below 40%
               simulation_state.generator(1).power_setpoint = gen_min_load;

            if simulation_state.pv(1).power_available > simulation_state.battery(1).max_charge_power && simulation_state.battery(1).state_of_charge_percent < 40
                    simulation_state.battery(1).power_setpoint = simulation_state.battery(1).max_charge_power;
            elseif simulation_state.pv(1).power_available < simulation_state.battery(1).max_charge_power && simulation_state.battery(1).state_of_charge_percent < 40 && simulation_state.battery(1).max_charge_power - simulation_state.pv(1).power_available > 0
               needed_to_charge = simulation_state.battery(1).max_charge_power - simulation_state.pv(1).power_available;
               simulation_state.battery(1).power_setpoint = needed_to_charge;
            end

        else
            %The generator cannot meet the load alone, therefore its output
            %is set at maximum load and the rest of the load will be
            %supplied with the batteries or the PV

            simulation_state.generator(1).power_setpoint = gen_power_available;
            actually_inverted_power = min(simulation_parameters.converter(1).inverter_capacity,(simulation_state.pv(1).power_setpoint-simulation_state.battery(1).power_setpoint).*simulation_parameters.converter(1).
```

```
inverter_efficiency/100);
        % Converter input and output
        if  simulation_state.ac_bus.load_requested-simulation_state.generator(1).power_setpoint > simulation_state.pv(1).power_setpoint
            %If the unmet load by the generator is larger  that the PV
            %production the batteries will be used
            if simulation_state.battery(1).state_of_charge_percent > 70
                simulation_state.battery(1).power_setpoint= -simulation_state.battery(1).max_discharge_power;
            else
                simulation_state.battery(1).power_setpoint= 0;
            end
            actually_inverted_power = min(simulation_parameters.converter(1).inverter_capacity,(simulation_state.pv(1).power_setpoint-simulation_state.battery(1).power_setpoint).*simulation_parameters.converter(1).inverter_efficiency/100);
            required_from_pv = min(simulation_state.ac_bus.load_requested-simulation_state.generator(1).power_setpoint, actually_inverted_power);
            simulation_state.converter(1).inverter_power_output = required_from_pv;
            simulation_state.converter(1).inverter_power_input = simulation_state.converter(1).inverter_power_output/(simulation_parameters.converter(1).inverter_efficiency/100);
        else %PV + generator are enough to meet the load.
            required_from_pv = min(simulation_state.ac_bus.load_requested-simulation_state.generator(1).power_setpoint, actually_inverted_power);
```

```
                    simulation_state.converter(1).inverter_power_output = required_from_pv;
                    simulation_state.converter(1).inverter_power_input = simulation_state.converter(1).inverter_power_output/(simulation_parameters.converter(1).inverter_efficiency/100);
                end
            end
        else
            %The generator is not required to meet the load, PV alone is
            %enough.
            simulation_state.converter(1).inverter_power_output = max(simulation_state.ac_bus.load_requested-simulation_state.generator(1).power_setpoint,0);
            simulation_state.converter(1).inverter_power_input =  simulation_state.converter(1).inverter_power_output/(simulation_parameters.converter(1).inverter_efficiency/100);

        end

else

%The second case of the firs IF condition starts here: when the batteries
%are below 20% charge at the beggining of the timestep.
%In this case if the system can meet the load without the batteries it will
%do so, and if there is enough excess energy it will be used to cahrge them


%--------------------------------------------------

    %The battery setpoint is initialized to be neither charging nor
    %discharging.
    simulation_state.battery(1).power_setpoint = 0;
 % The energy after the inverter is defined
    actually_inverted_power = min(simulation_parameters.converter(1).inverter_capacity,(simulation_state.
```

```
pv(1).power_setpoint-simulation_state.battery(1).power_setpoint).*simulation_parameters.converter(1).inverter_efficiency/100);
% The generator will operate when the PV power alone is not enoguh to meet
% the load or when we want to minimize the converter use
    if simulation_parameters.has_generator==true && (simulation_state.ac_bus.load_requested-actually_inverted_power)>0
        gen_power_available = simulation_state.generator(1).power_available;
        gen_min_load = simulation_parameters.generator_list(1).minimum_load;
        electrical_load = simulation_state.ac_bus.load_requested;
        load_unmet_after_pv = simulation_state.ac_bus.load_requested-actually_inverted_power;
        if gen_power_available > electrical_load && gen_min_load < electrical_load
            %The generator can meet the load at minimum load.
            simulation_state.generator(1).power_setpoint = max(load_unmet_after_pv,gen_min_load); %If the unmet load after the PV is samller than the minimum load it generate the minimum
            %The batteries charging regime is defined accodring to the
            %system needs
            if load_unmet_after_pv < gen_min_load
            required_from_pv = min(simulation_state.ac_bus.load_requested-simulation_state.generator(1).power_setpoint,actually_inverted_power);
            simulation_state.converter(1).inverter_power_output = required_from_pv;
            simulation_state.converter(1).inverter_power_input =  simulation_state.converter(1).inverter_power_output/(simulation_parameters.converter(1).inverter_efficiency/100);
            else
            required_from_batteries= simulation_state.ac_bus.load_requested-simulation_state.generator(1).power_setpoint-(simulation_state.pv(1).power_setpoint*simulation_parameters.converter(1).
```

```
inverter_efficiency/100);
            if required_from_batteries < 0 && (-required_from_batteries./(simulation_parameters.converter(1).inverter_efficiency/100)) < simulation_state.battery(1).max_charge_power
              simulation_state.battery(1).power_setpoint = -required_from_batteries./(simulation_parameters.converter(1).inverter_efficiency/100);
              actually_inverted_power = min(simulation_parameters.converter(1).inverter_capacity,(simulation_state.pv(1).power_setpoint-simulation_state.battery(1).power_setpoint).*simulation_parameters.converter(1).inverter_efficiency/100);
            elseif required_from_batteries < 0 && (-required_from_batteries./(simulation_parameters.converter(1).inverter_efficiency/100)) > simulation_state.battery(1).max_charge_power
              simulation_state.battery(1).power_setpoint = simulation_state.battery(1).max_charge_power;
            end
            end
            %Here ends what is required from the batteries.

            % The input and output of the converter are defined
            converted_power_required = min(simulation_state.ac_bus.load_requested-simulation_state.generator(1).power_setpoint,actually_inverted_power);
            simulation_state.converter(1).inverter_power_output = converted_power_required;
            simulation_state.converter(1).inverter_power_input =  simulation_state.converter(1).inverter_power_output/(simulation_parameters.converter(1).inverter_efficiency/100);
```

```

        elseif gen_power_available > electrical_load %()()()
            % The genreator can meet the load at minimum power and the
            % excess electricity is used to charge the batteries

            simulation_state.generator(1).power_setpoint = gen_min_load;

            if simulation_state.pv(1).power_available > simulation_state.battery(1).max_charge_power && simulation_state.battery(1).state_of_charge_percent < 40
                    simulation_state.battery(1).power_setpoint = simulation_state.battery(1).max_charge_power;
            elseif simulation_state.pv(1).power_available < simulation_state.battery(1).max_charge_power && simulation_state.battery(1).state_of_charge_percent < 40 && simulation_state.battery(1).max_charge_power - simulation_state.pv(1).power_available > 0
                needed_to_charge = simulation_state.battery(1).max_charge_power - simulation_state.pv(1).power_available;
                simulation_state.battery(1).power_setpoint = needed_to_charge;
            end

        else
            %The generator is unable to meet the demand at minimum load
            %therefore its ouput is maximized and the rest of the load will
            %be met by either the PV or the batteries.
            simulation_state.generator(1).power_setpoint = gen_power_available;
            actually_inverted_power = min(simulation_parameters.converter(1).inverter_capacity,(simulation_state.pv(1).power_setpoint-simulation_state.battery(1).power_setpoint).*
```

```
                    simulation_parameters.converter(1).inverter_efficiency/100);
                % The input and output of the converter are defined
                    required_from_pv = min(simulation_state.ac_bus.load_requested-simulation_state.generator(1).power_setpoint,actually_inverted_power);
                    simulation_state.converter(1).inverter_power_output = required_from_pv;
                    simulation_state.converter(1).inverter_power_input = simulation_state.converter(1).inverter_power_output/(simulation_parameters.converter(1).inverter_efficiency/100);

        end
    end
end

%%-----------------------------------------------
% Here start the definitions of the parameteres required from HOMER Pro

% The "Operating Capacity Served" parameter is defined
    if simulation_state.generator(1).power_setpoint >0
        simulation_state.ac_bus.operating_capacity_served = simulation_state.generator(1).power_available;
    end
    simulation_state.dc_bus.operating_capacity_served = simulation_state.pv(1).power_available-simulation_state.battery(1).power_setpoint;
 %-----------------------------------------------------
% The "Capacity Shortage" parameter is defined
    DC_remaining_cap = simulation_state.dc_bus.operating_capacity_requested-simulation_state.dc_bus.operating_capacity_served;
    AC_remaining_cap =  simulation_state.ac_bus.operating_capacity_requested-simulation_state.ac_bus.operating_capacity_served;
    % If DC_remaining_cap is <=0 the capactigy is satisfied
```

```
    % IF DC_remaining_capis >0 There is not enough capcity to meet the
    % required load

    if (DC_remaining_cap>0 && AC_remaining_cap<=0)
         %The remianing AC power is converted into DC
        AC_remaining_cap=AC_remaining_cap*(-1);
        simulation_state.ac_bus.capacity_shortage=0;
        simulation_state.dc_bus.capacity_shortage=max(DC_remaining_cap - min(simulation_parameters.converter(1).rectifier_capacity, AC_remaining_cap*simulation_parameters.converter(1).rectifier_efficiency/100),0);
        if simulation_state.dc_bus.capacity_shortage>0 && simulation_state.battery(1).power_setpoint >0
            simulation_state.battery(1).power_setpoint=0;
            simulation_state.dc_bus.operating_capacity_served = simulation_state.pv(1).power_available;
            simulation_state.dc_bus.capacity_shortage=max(simulation_state.dc_bus.operating_capacity_requested-simulation_state.dc_bus.operating_capacity_served,0);
        end
    end

    %If the DC demand is met but not the AC demand:
    if (DC_remaining_cap<=0 && AC_remaining_cap>0)
         %The leftover DC power is converted into AC
        DC_remaining_cap=DC_remaining_cap*(-1);
        simulation_state.dc_bus.capacity_shortage=0;
        simulation_state.ac_bus.capacity_shortage=max(AC_remaining_cap - min(simulation_parameters.converter(1).inverter_capacity, DC_remaining_cap*simulation_parameters.converter(1).inverter_efficiency/100),0);
        % Switch on the generator if AC operating capacity is still not satisfied
        if simulation_state.ac_bus.capacity_shortage>0 && simulation_state.generator(1).power_setpoint==0
            simulation_state.generator(1).power_setpoint = simulation_parameters.generator_list(1).minimum_load;
            %If the load is met with the generator it is not required to
```

```
            %invert DC power, and the inverter input and output are set to
            %zero

            if (simulation_state.generator(1).power_setpoint >=simulation_state.ac_bus.load_requested)
                simulation_state.converter(1).inverter_power_output = 0;
                simulation_state.converter(1).inverter_power_input = 0;
            else
                required_from_pv = min(simulation_state.ac_bus.load_requested-simulation_state.generator(1).power_setpoint, actually_inverted_power);
                simulation_state.converter(1).inverter_power_output = required_from_pv;
                simulation_state.converter(1).inverter_power_input = simulation_state.converter(1).inverter_power_output/(simulation_parameters.converter(1).inverter_efficiency/100);
            end
            simulation_state.ac_bus.operating_capacity_served = simulation_state.generator(1).power_available;
            simulation_state.ac_bus.capacity_shortage=max(simulation_state.ac_bus.operating_capacity_requested-simulation_state.ac_bus.operating_capacity_served,0);
        end
    else
             simulation_state.ac_bus.capacity_shortage=0;
             simulation_state.dc_bus.capacity_shortage=0;

    end

 %----------------------------------------------------
% The "Load Served" parameter is defined
    power_to_ac_bus = simulation_state.generator(1).power_setpoint +  simulation_state.converter(1).
```

```
        inverter_power_output;
    simulation_state.ac_bus.load_served =  min(
        simulation_state.ac_bus.load_requested,
        power_to_ac_bus);
    if simulation_state.battery(1).power_setpoint > 0 &&
         simulation_state.battery(1).
        state_of_charge_percent < 100
        simulation_state.dc_bus.load_requested=
            simulation_state.battery(1).power_setpoint;
        power_to_dc_bus=simulation_state.pv(1).
            power_setpoint;
        simulation_state.dc_bus.load_served =
            power_to_dc_bus;
    end
    simulation_state.dc_bus.load_served = 0;
    simulation_state.primary_load(1).load_served =
        simulation_state.ac_bus.load_served;

 %-----------------------------------------------
% The parameter "Unmet Load" is defined

    simulation_state.ac_bus.unmet_load = max(
        simulation_state.ac_bus.load_requested -
        simulation_state.ac_bus.load_served, 0);
    %simulation_state.dc_bus.unmet_load = max(
        simulation_state.dc_bus.load_requested -
        simulation_state.dc_bus.load_served, 0);
    % In this case there is no load on the DC bus
 %-----------------------------------------------
% The paramètter "Excess Electricity" is defined

   simulation_state.ac_bus.excess_electricity = max(
      simulation_state.generator(1).power_setpoint -
      simulation_state.converter(1).
      rectifier_power_input +  simulation_state.
      converter(1).inverter_power_output -
      simulation_state.ac_bus.load_requested,0);
   simulation_state.dc_bus.excess_electricity = max(
      simulation_state.pv(1).power_available-
      simulation_state.converter(1).inverter_power_input
       +  simulation_state.converter(1).
      rectifier_power_output-simulation_state.battery(1)
      .power_setpoint,0);

end
```

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